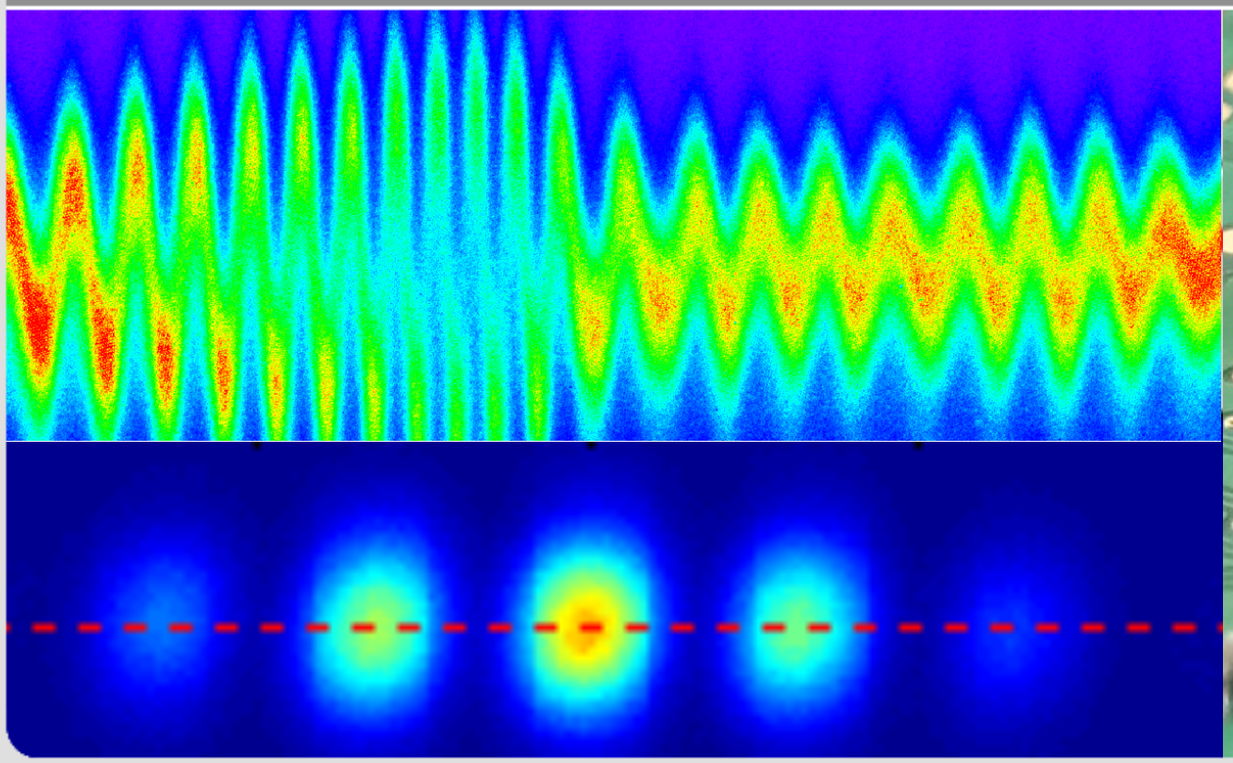
Karlsruhe Institute of Technology

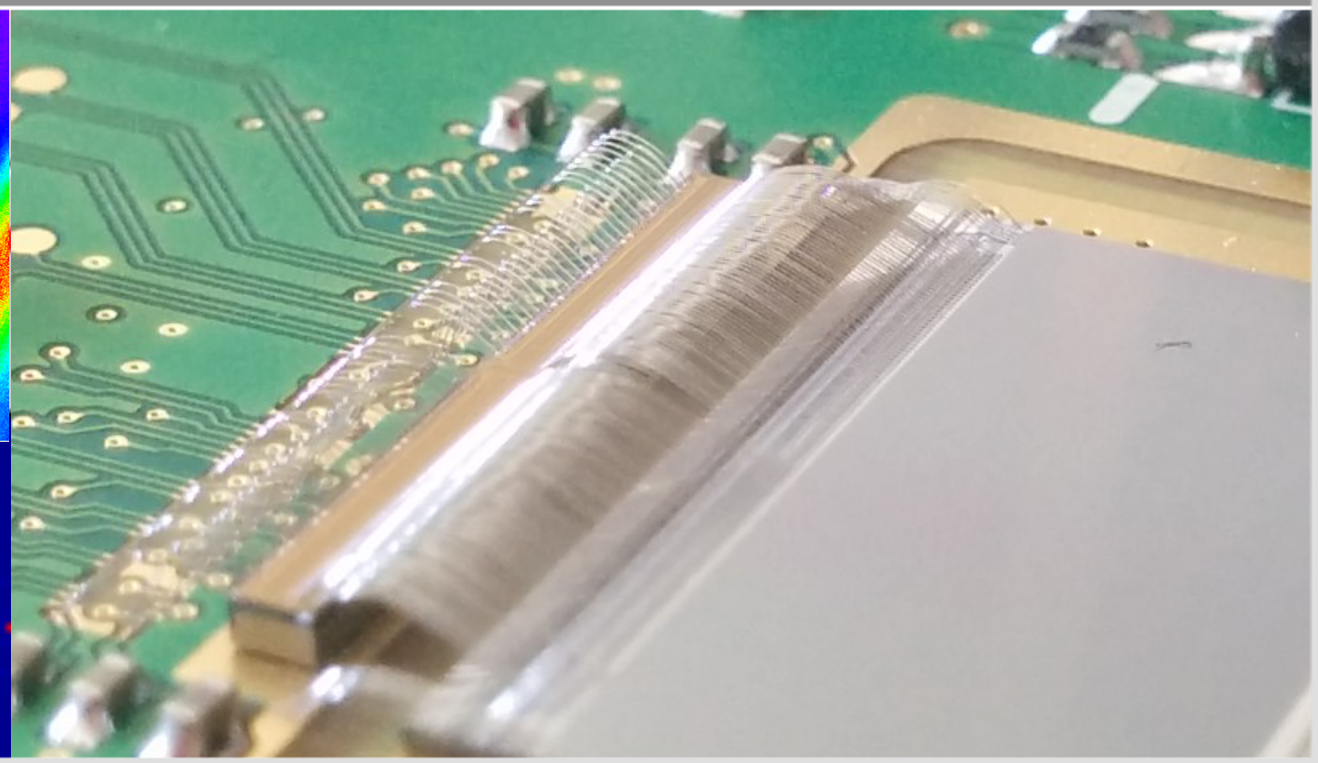
International Beam Instrumentation Conference IBIC
11 - 15 September 2016 Barcelona

Micro-bunching measurement techniques in storage rings

Anke-Susanne Müller

INSTITUTE FOR BEAM PHYSICS AND TECHNOLOGY (IBPT)





Micro-bunching instability

- Complex and nonlinear dynamics in longitudinal phase space
- Can lead to bursts of very intense, coherent synchrotron radiation
- Observation of, e.g.,
  - longitudinal bunch profiles [“direct”]
  - emitted (coherent) radiation [“indirect”]
- Relevant timescales:
  - bunch length
  - dimension of micro-structures
  - distinguish between individual bunches
  - follow bursting behavior
  - observe slow changes (e.g., with current)
- Diagnostics requirements:
  - high resolution (ps) - high rate (500 MHz) - long term observation (secs - hrs)

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  - follow bursting behavior — **10 ms**
  - observe slow changes (e.g., with current) — **sec - hrs**
- Diagnostics requirements:
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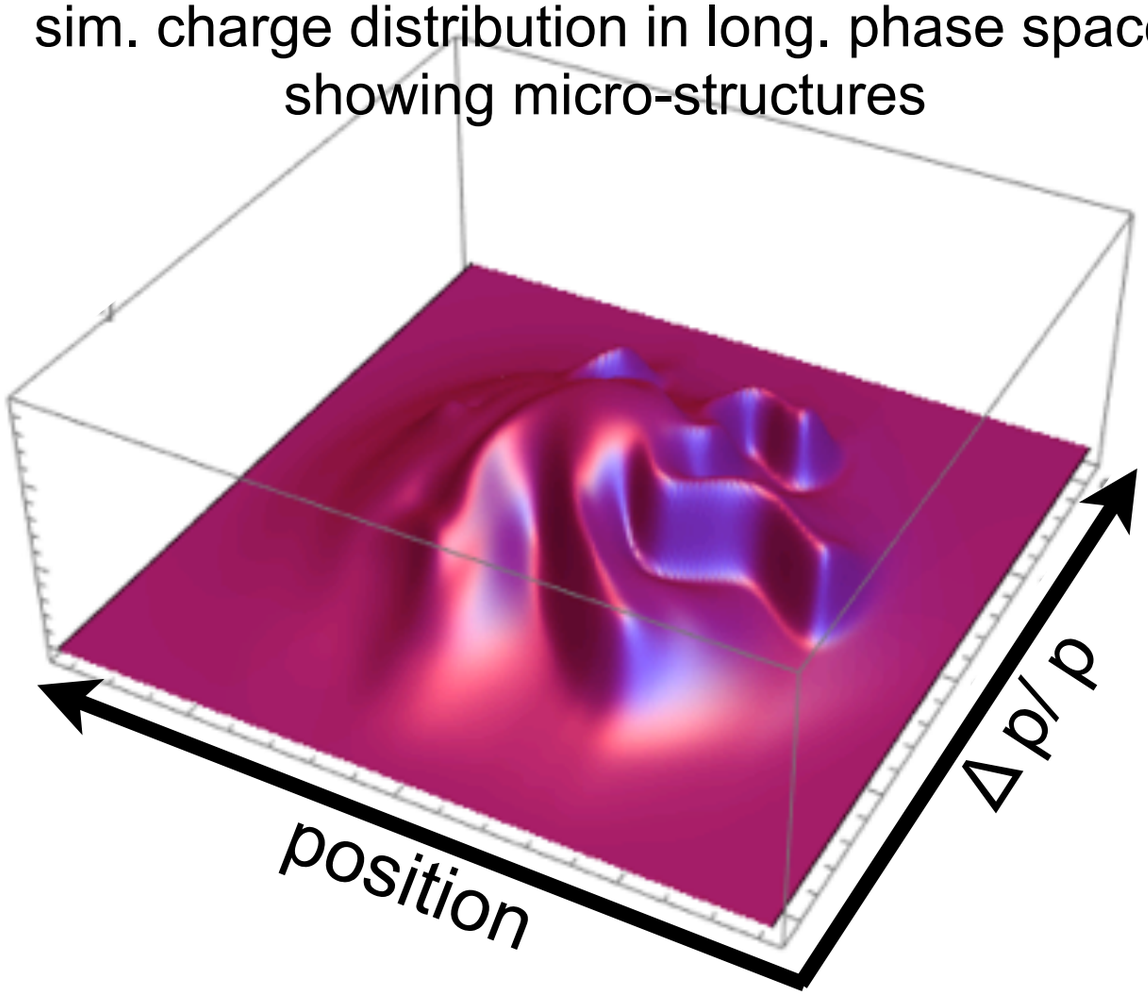
Longitudinal phase space

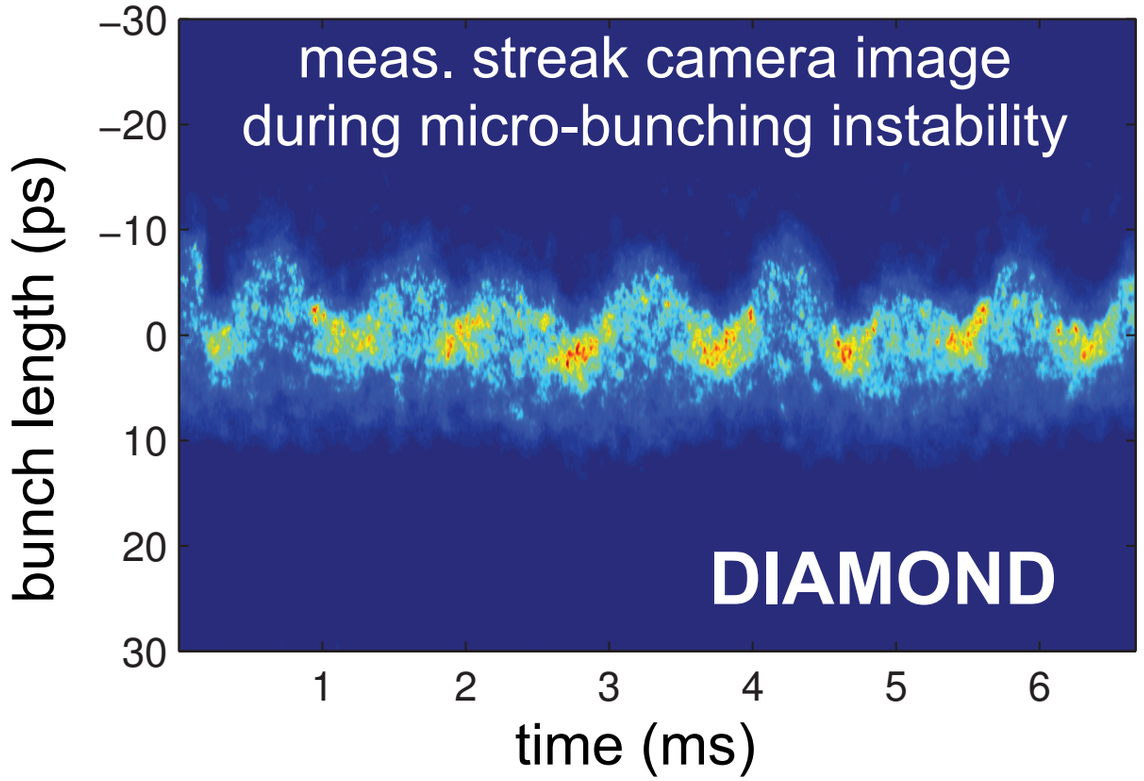
- Micro-bunching instability:

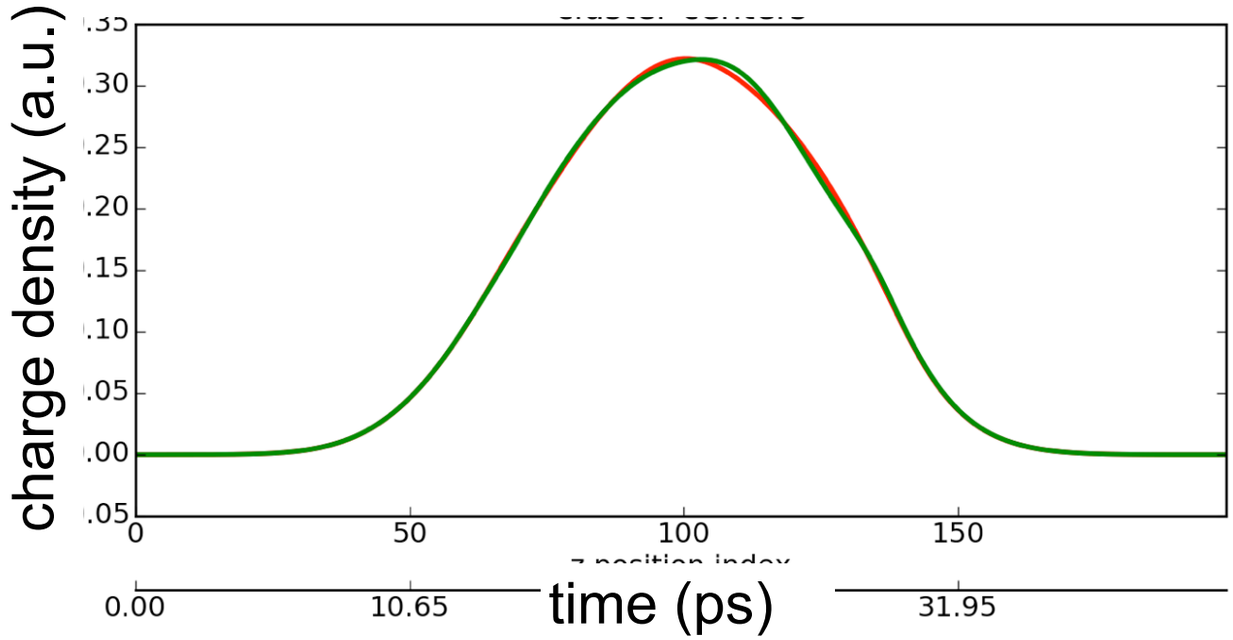
sim. charge distribution in long. phase space showing micro-structures



courtesy T. Boltz

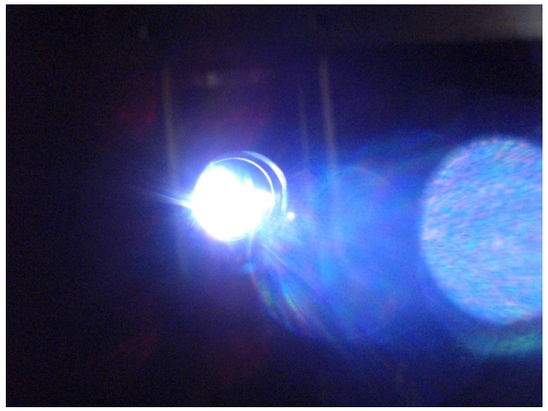
I.P.S. Martin et al., IPAC2015, MOPMA003

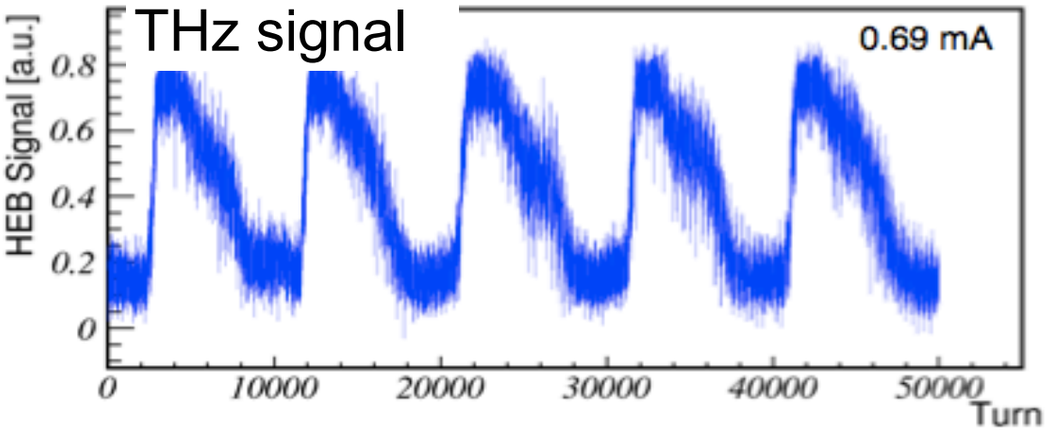




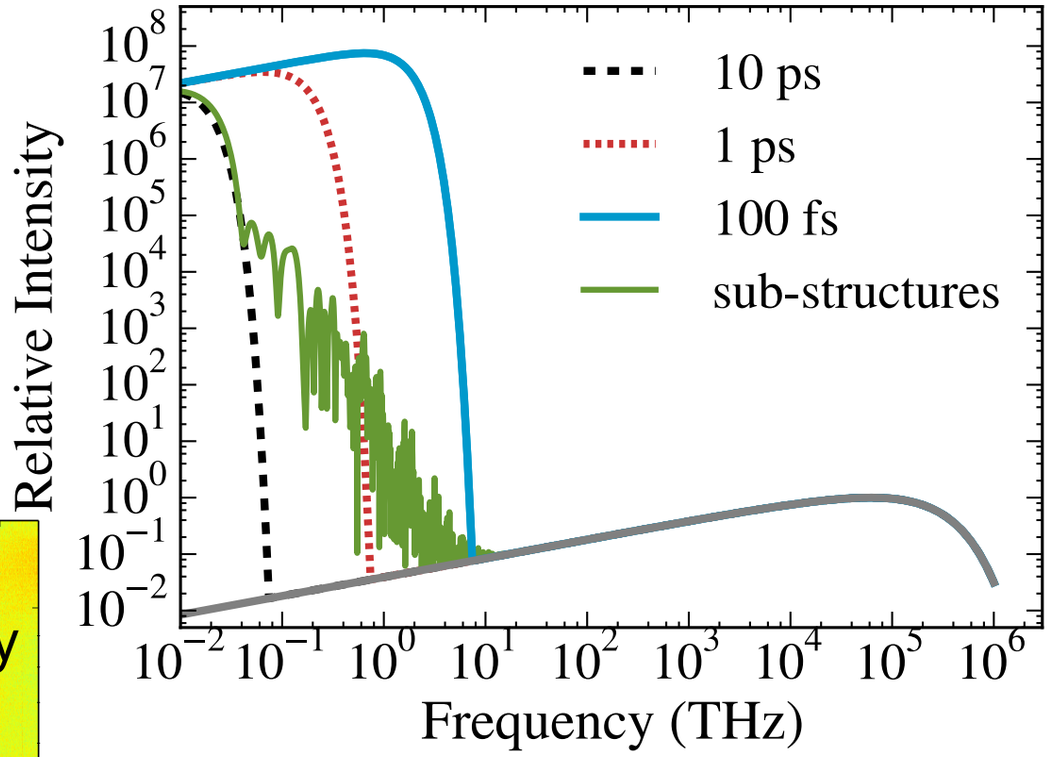
sim. long. bunch profile (very small variation!)

Indirect observation: emitted THz radiation



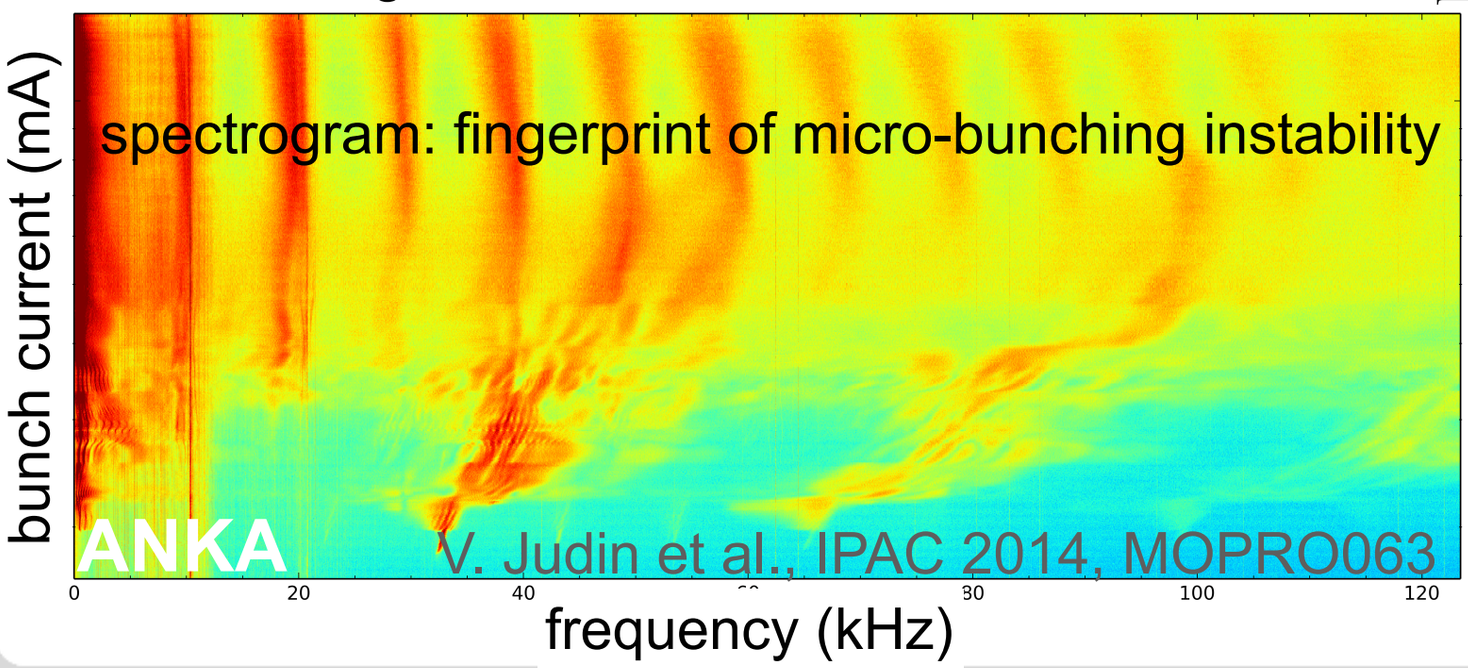


V. Judin et al., IPAC2010, WEPEA021



spectrum: dimension of typical structures

FFT of THz signal as a function of bunch current



Classification of techniques - a try

Karlsruhe Institute of Technology

THz techniques time domain

- spectrograms and information extracted from them
- “finger print” of instability

EO techniques far field

- detect photons from emitted THz pulse
- measure ‘wake fields’ (EOS) and bunch profiles (EOSD)

THz techniques frequency domain

- signature of sub-structures
- single-shot acquisition of radiation spectrum maps bunch dynamics

EO techniques near field

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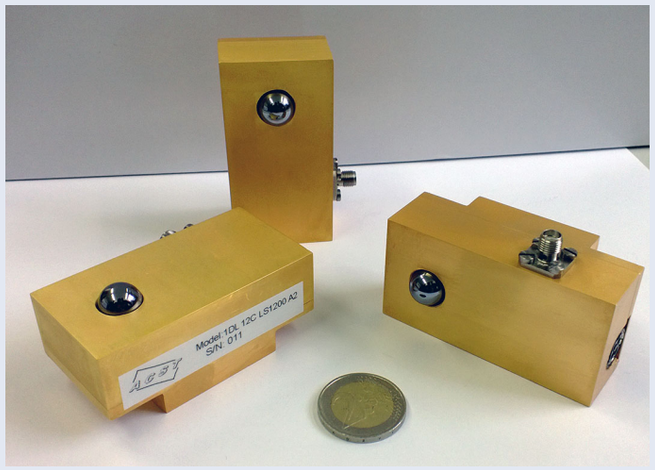
THz detectors - example ANKA

Quasi-optical broadband detector



room temperature

response time $<$200ps

50 GHz up to 1 THz

based on schottky diode

ACST (acst.de)

Hot Electron Bolometer (NbN)

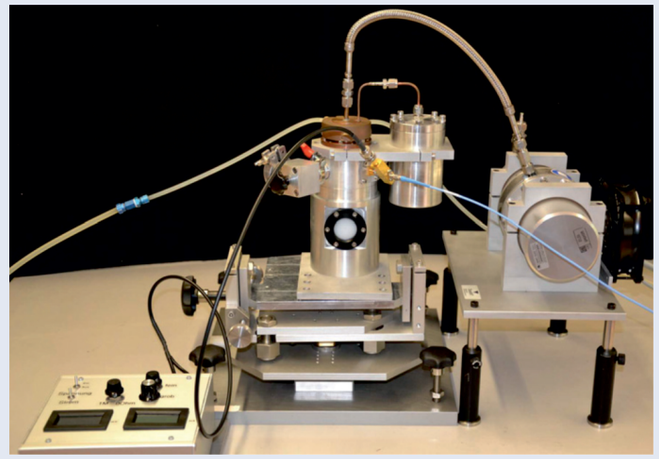
cryogenic (LHe)

response time $<$165ps

200 GHz up to 4 THz

DLR high sensitivity [2]

YBCO detector



cryogenic (LN2)

response time $<$15ps

30 GHz up to 2.5 THz

(KIT - IMS)

J. Raasch [1]

- Resolve intensity of each bunch (minimal bunch spacing 2 ns)

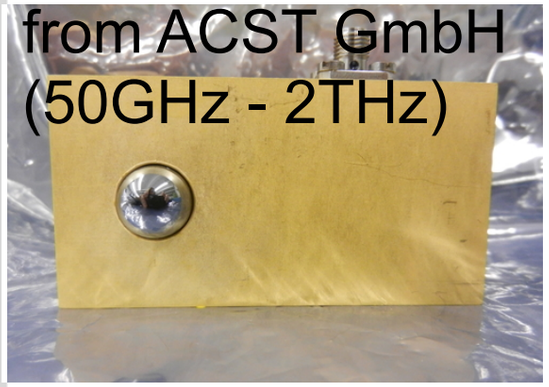
[1] Thoma, P.; Raasch, J.; et al.; IEEE Trans. Appl. Supercond., vol.23, no.3, pp.2400206,2400206, June 2013

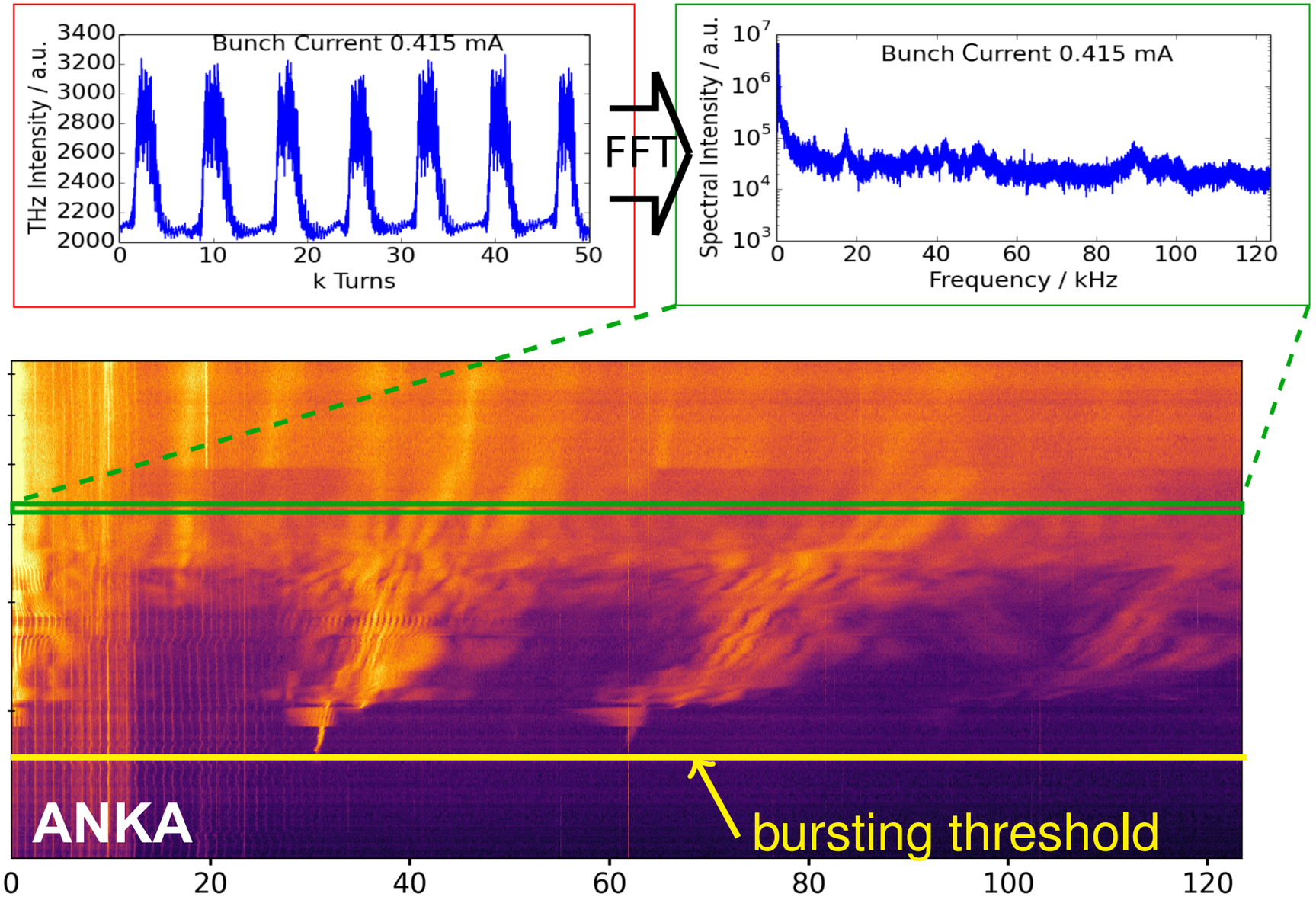
[2] Yu.P. Gousev, G.N. Gol'tsman, A.D. Semenov et al. Broadband ultrafast superconducting NbN detector for electromagnetic radiation. J. Appl. Phys., 75:3695, 1994.

courtesy M. Brosi

From THz signal to spectrogram

- Detector: must resolve bunches with a bunch spacing of 2 ns
  - e.g., zero-biased quasi-optical Schottky barrier diode



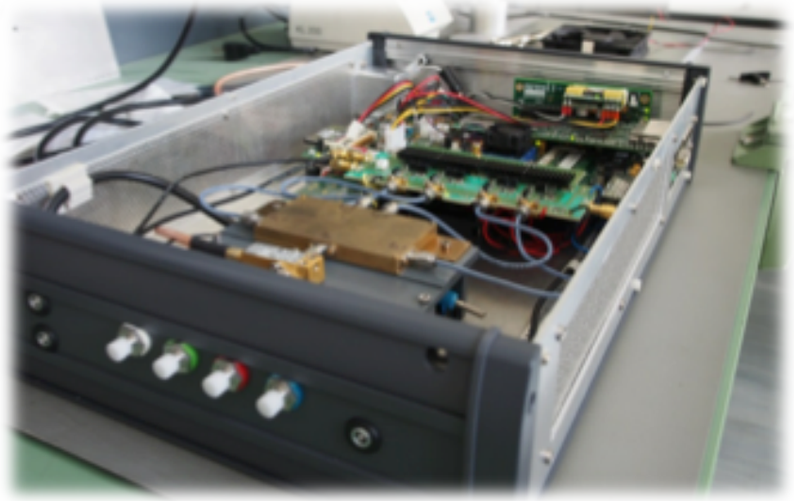


M. Brosi et al., IPAC 2016, TUPOR006

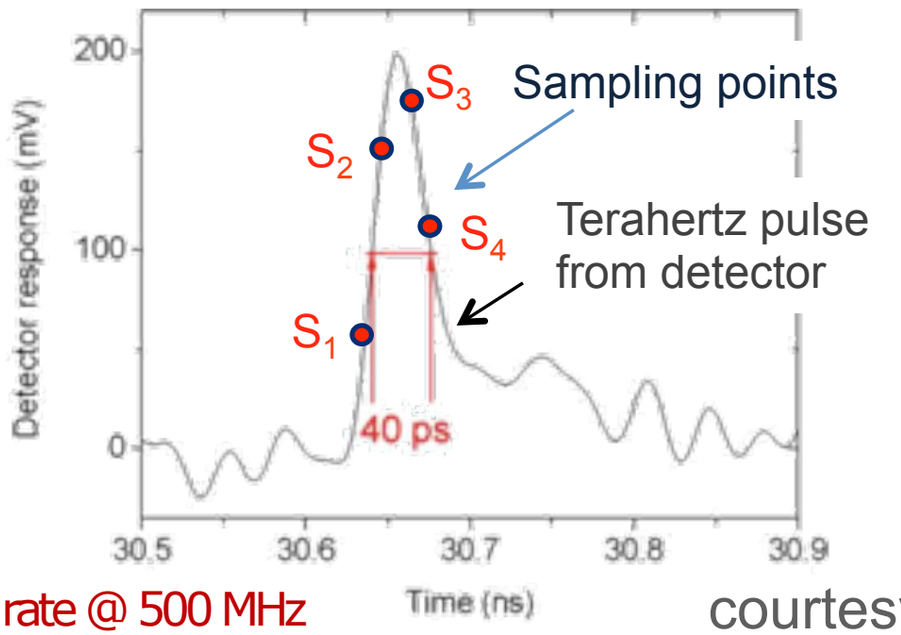
M. Brosi et al., arXiv:1605.00536

The faster way: “Snapshot” measurements with the KAPTURE system

- **KAPTURE: KA**rlsruhe **P**ulse **T**aking **U**ltra-Fast **R**eadout **E**lectronics
  - Readout system compatible with: YBCO, HEB, and Schottky diode detectors
  - Pulse amplitude and arrive time measurements with “mv” and “ps” accuracy
  - Simultaneous acquisition of all buckets turn-by-turn in streaming mode
  - Continuous acquisition for long observation time.
  - Real-time data evaluation by GPUs

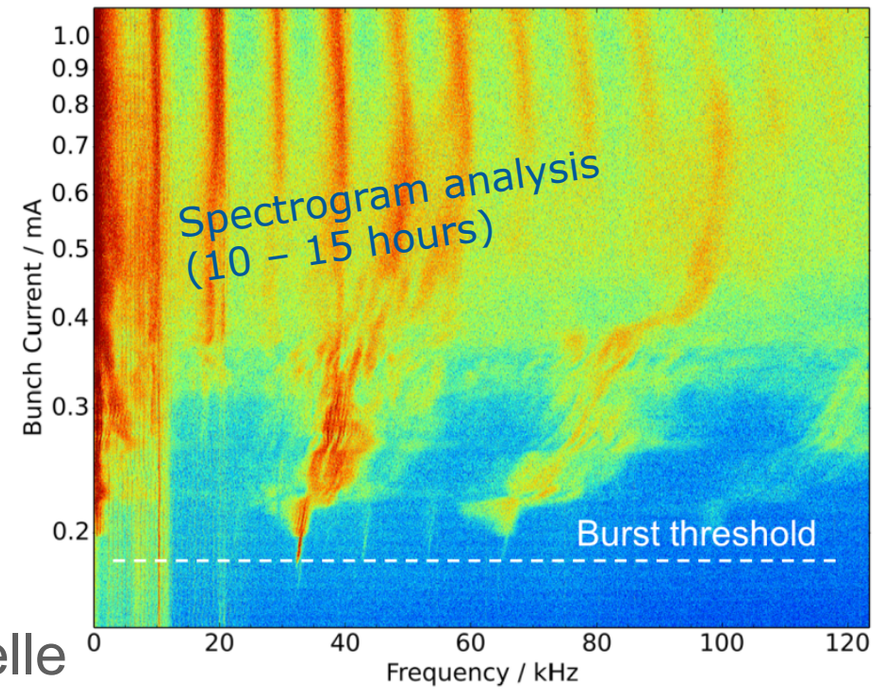


KAPTURE - Basic concept



Pulse rate @ 500 MHz

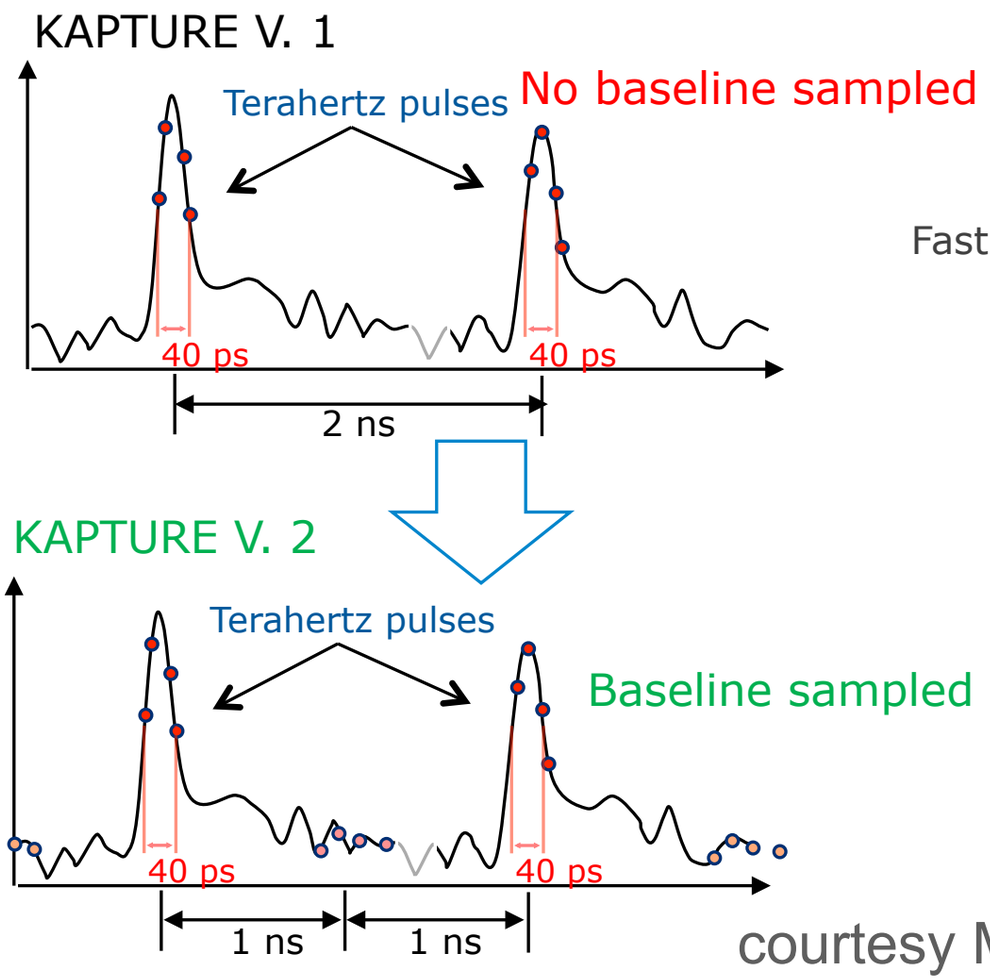
Frequency behaviour of CSR @ different bunch current

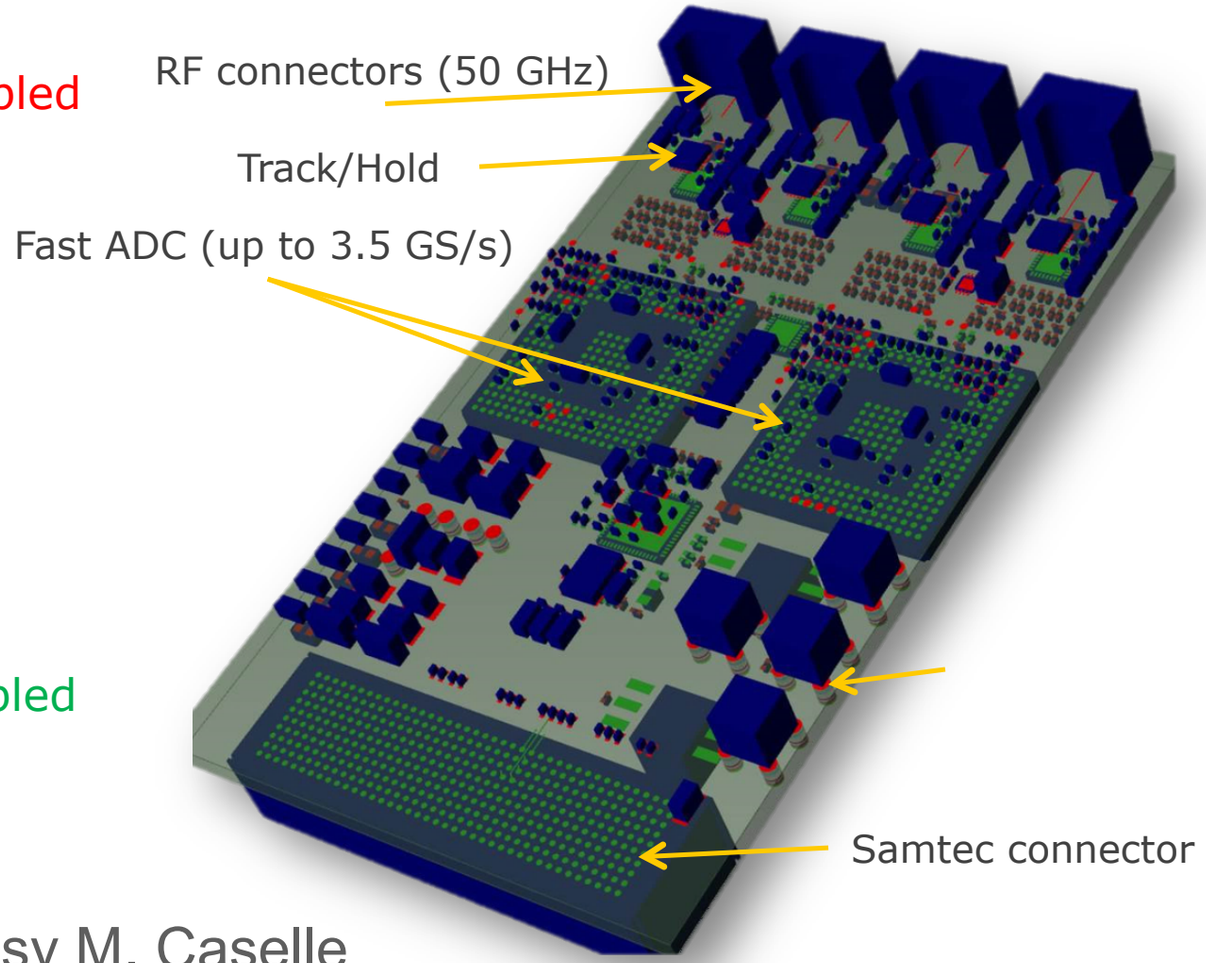


courtesy M. Caselle

KAPTURE v2: compact+high sampling rate design

- Target design:
  - Very wide operating frequency from 0.2 to 3.5 GS/s per sampling channel (ANKA @ 1 GS/s)
  - Modular design for multiple KAPTURE connections ➜ to extend the sampling points over 4 samples
  - PCB size reduced by factor 2, two KAPTURE connected to one readout card
  - Form factor mechanically/electrically compatible with µTCA system



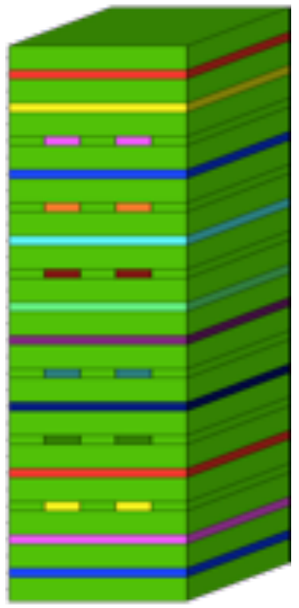


courtesy M. Caselle

KAPTURE – 2. PCB technology

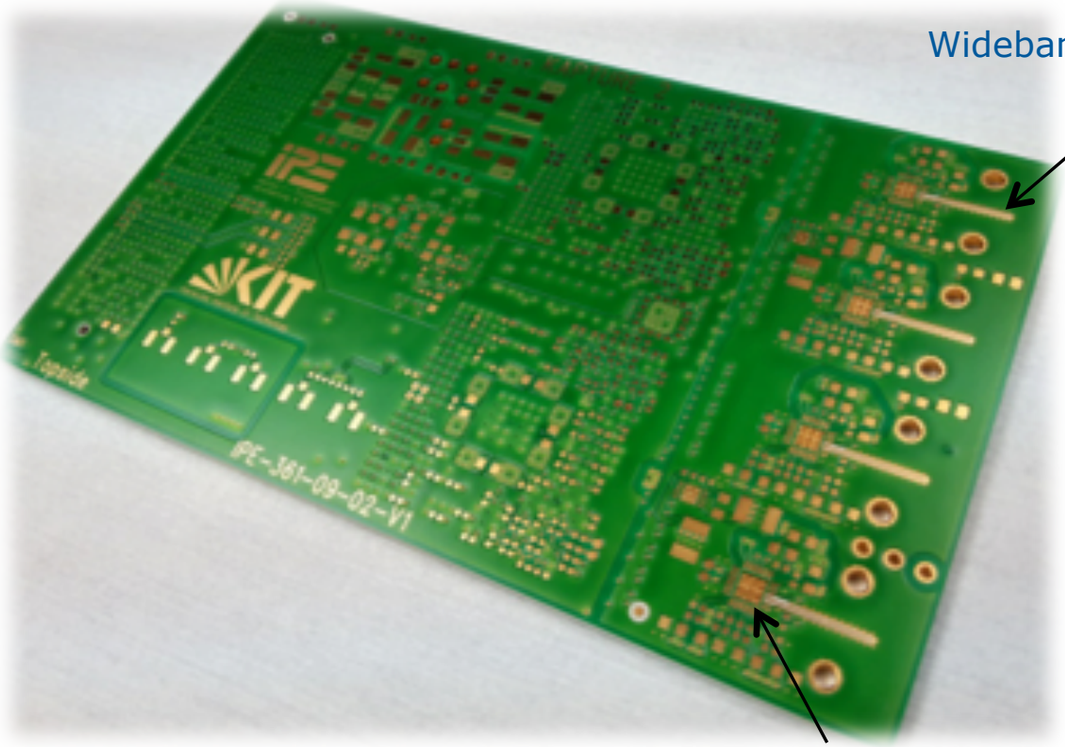
PWs/GNDs

CPW transmission lines



16 metal layers
RF substrate Roger 4003

Wideband transmission lines

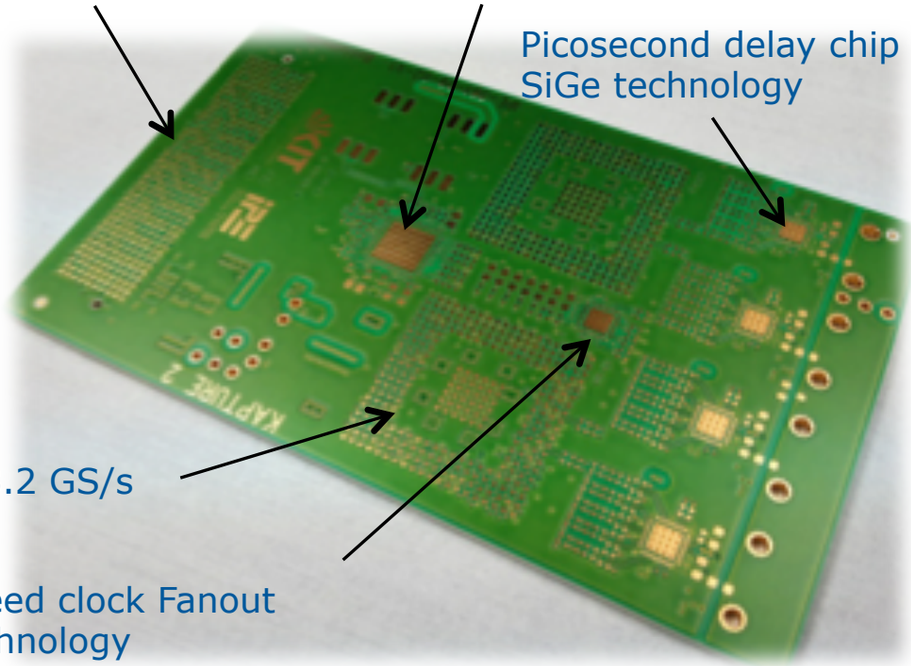


Front-end electronics
SiGe technology

Samtec FMC connector

Jitter cleaner PLL (123 fs)

Picosecond delay chip
SiGe technology



Fast ADC up to 3.2 GS/s

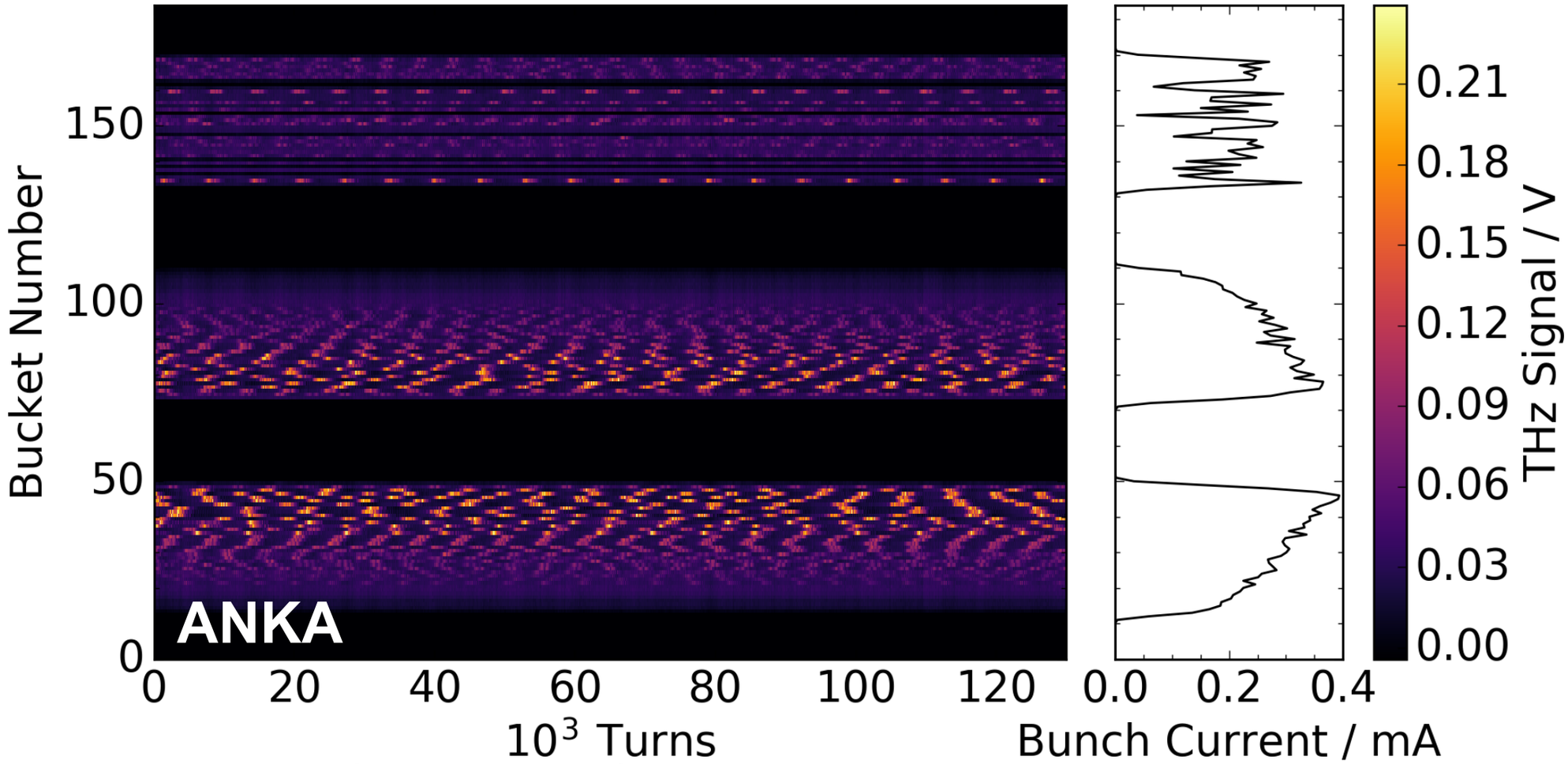
High-speed clock Fanout
SiGe technology

First prototype will be ready:
mid of September

courtesy M. Caselle

From THz signal to spectrogram with KAPTURE

- Cover beam current range with special filling pattern
- read out each bunch's time signal with KAPTURE



M. Brosi et al., IPAC 2016, TUPOR006

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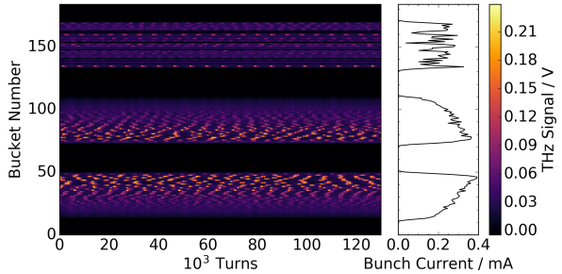
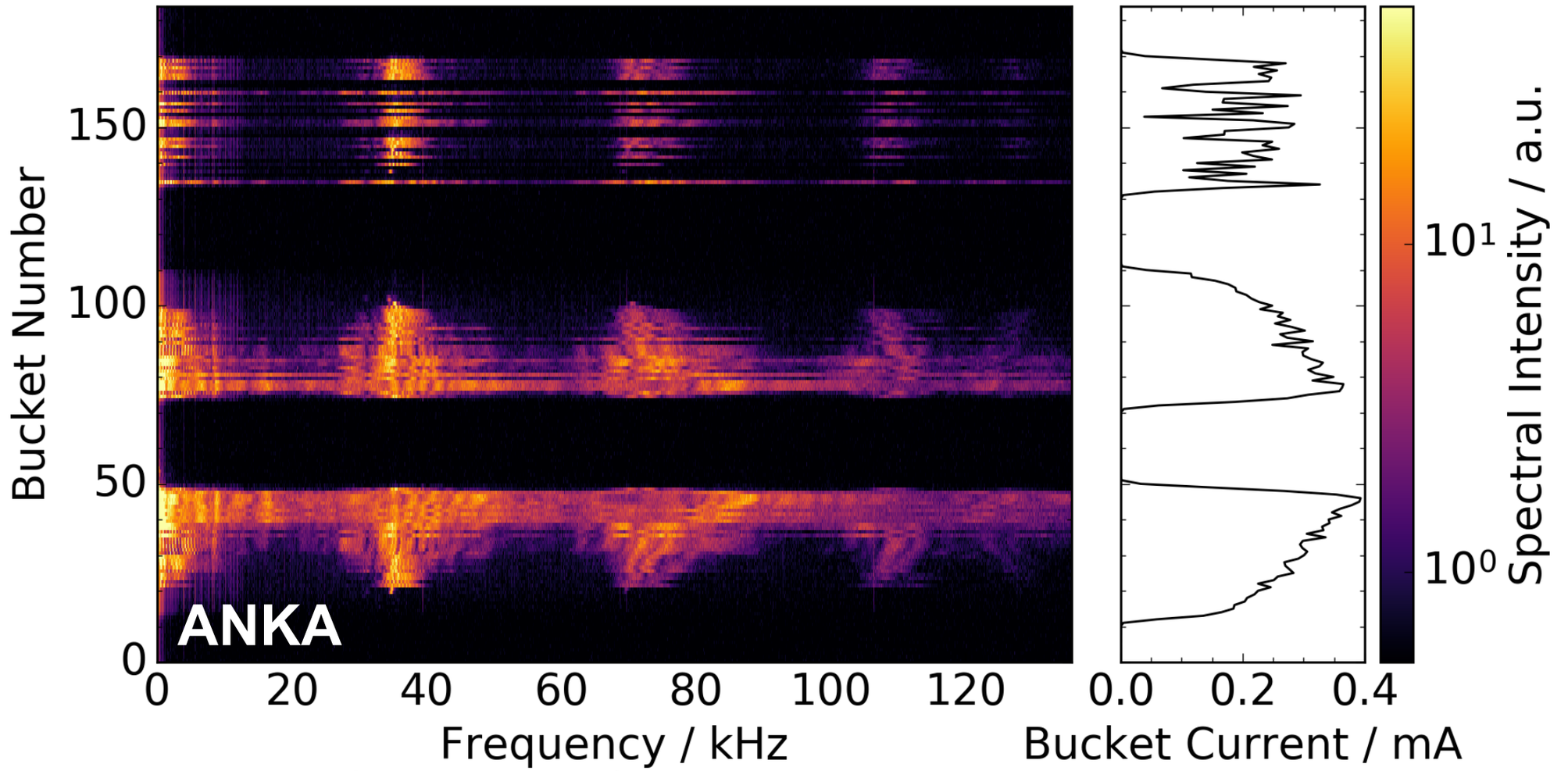


- FFT for each bunch's signal:



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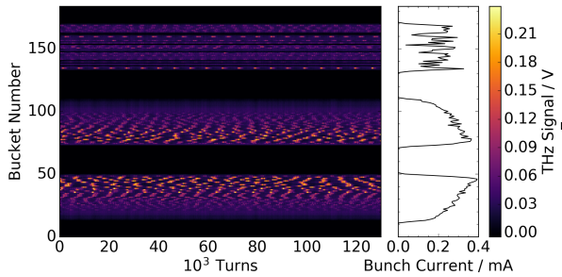
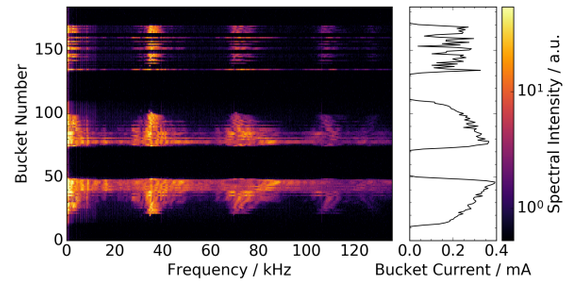
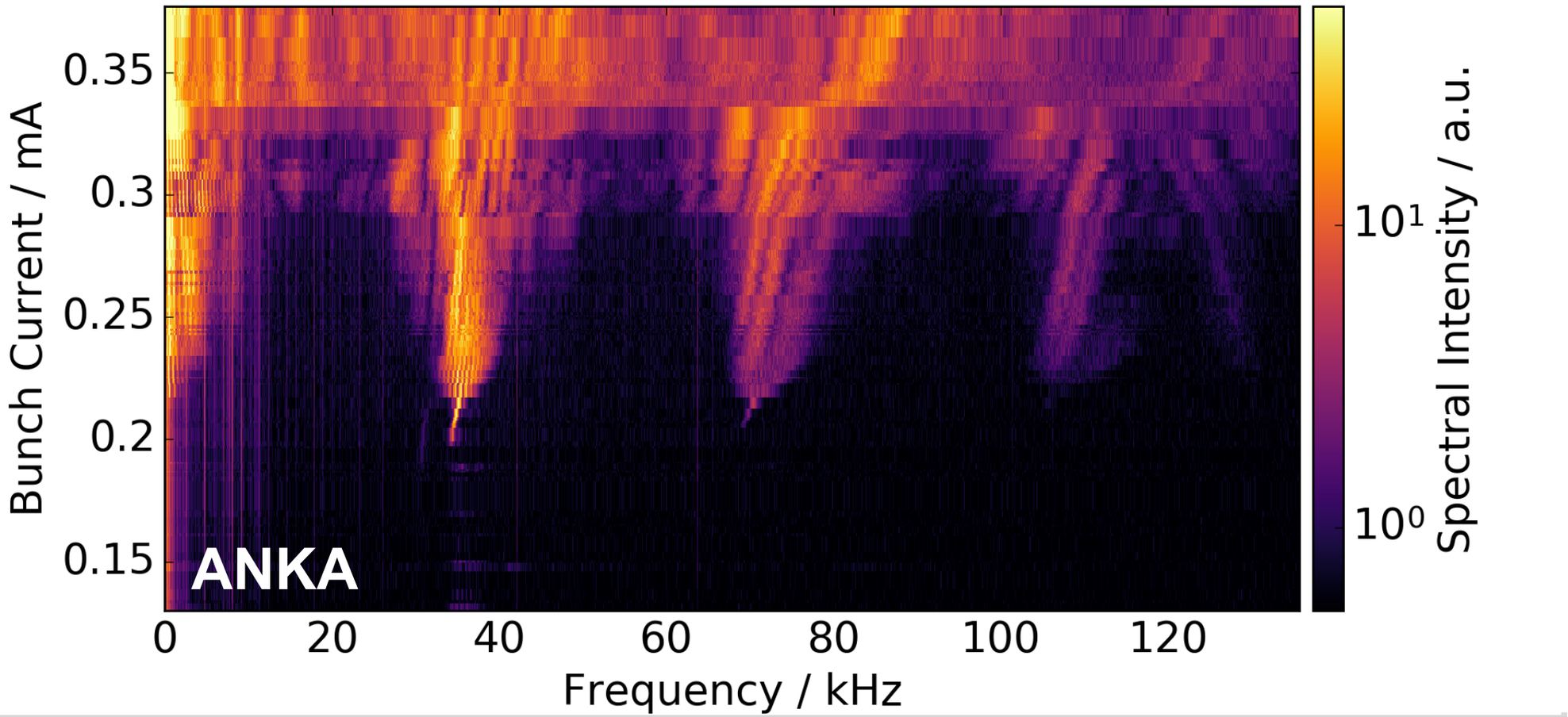




- Sorted by bunch current:



M. Brosi et al., IPAC 2016, TUPOR006

Classification of techniques - a try

THz techniques time domain

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- “finger print” of instability

EO techniques far field

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EO techniques near field

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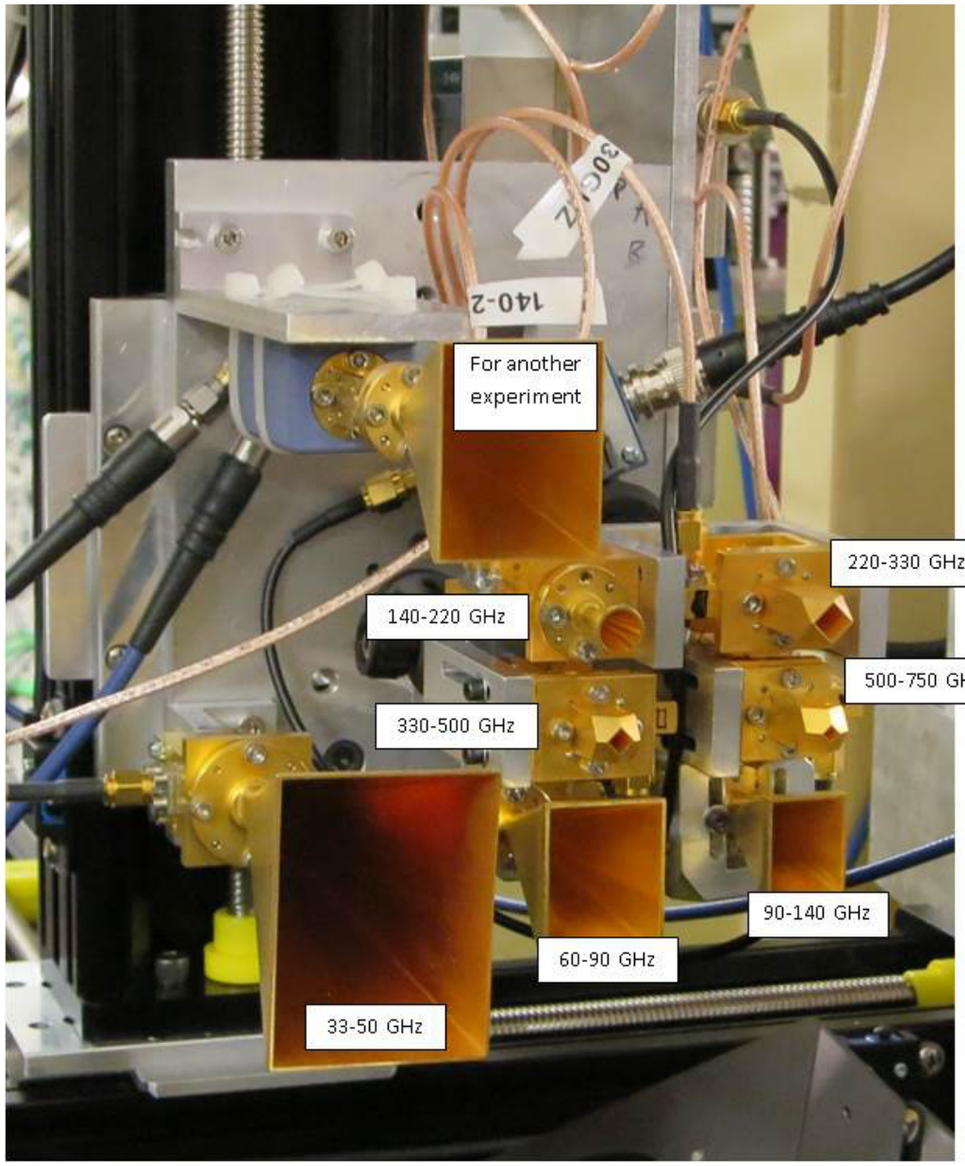
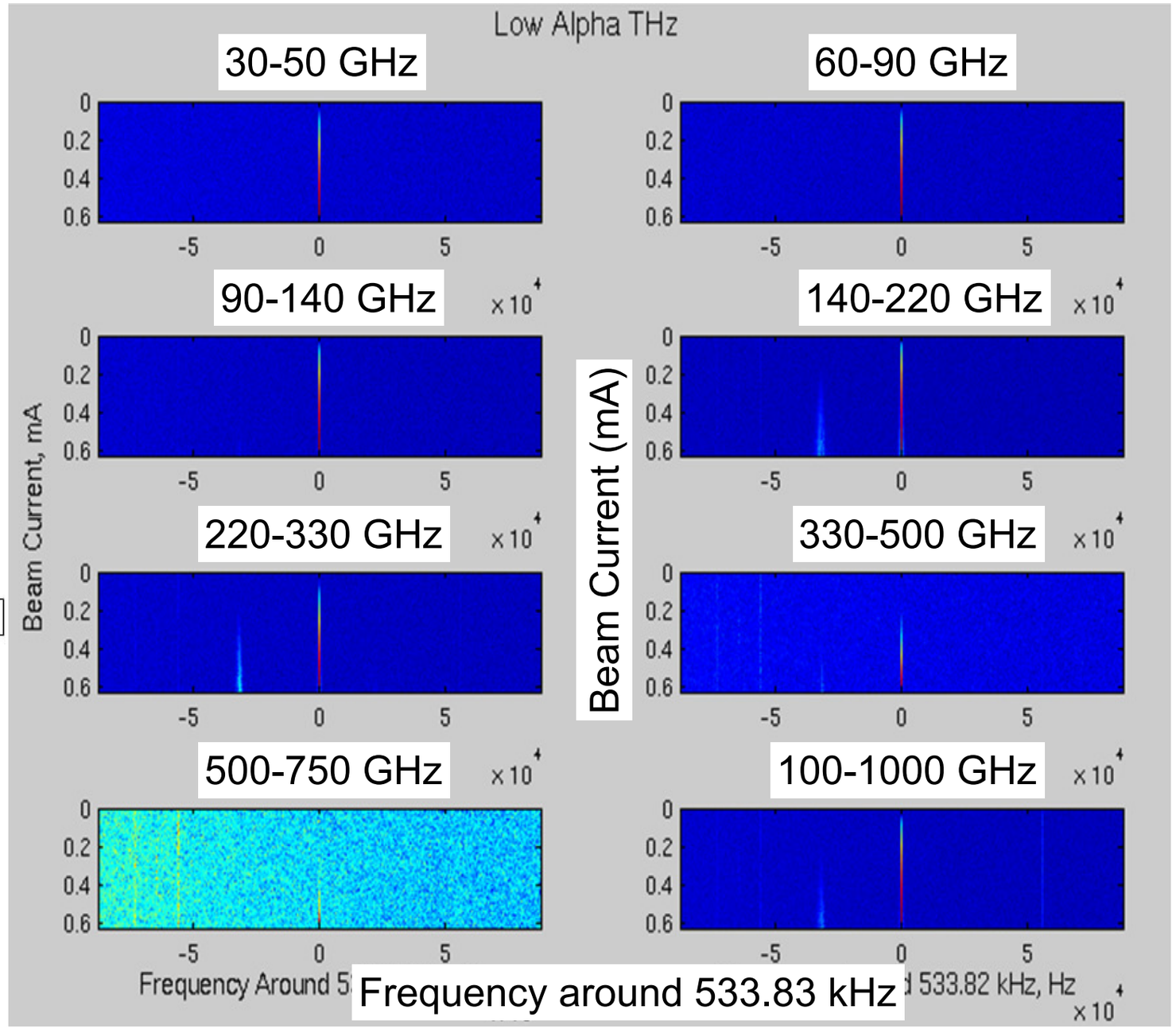
Single-shot spectrometer

- Multi-band mm wave detectors
- Measurements at DIAMOND LS

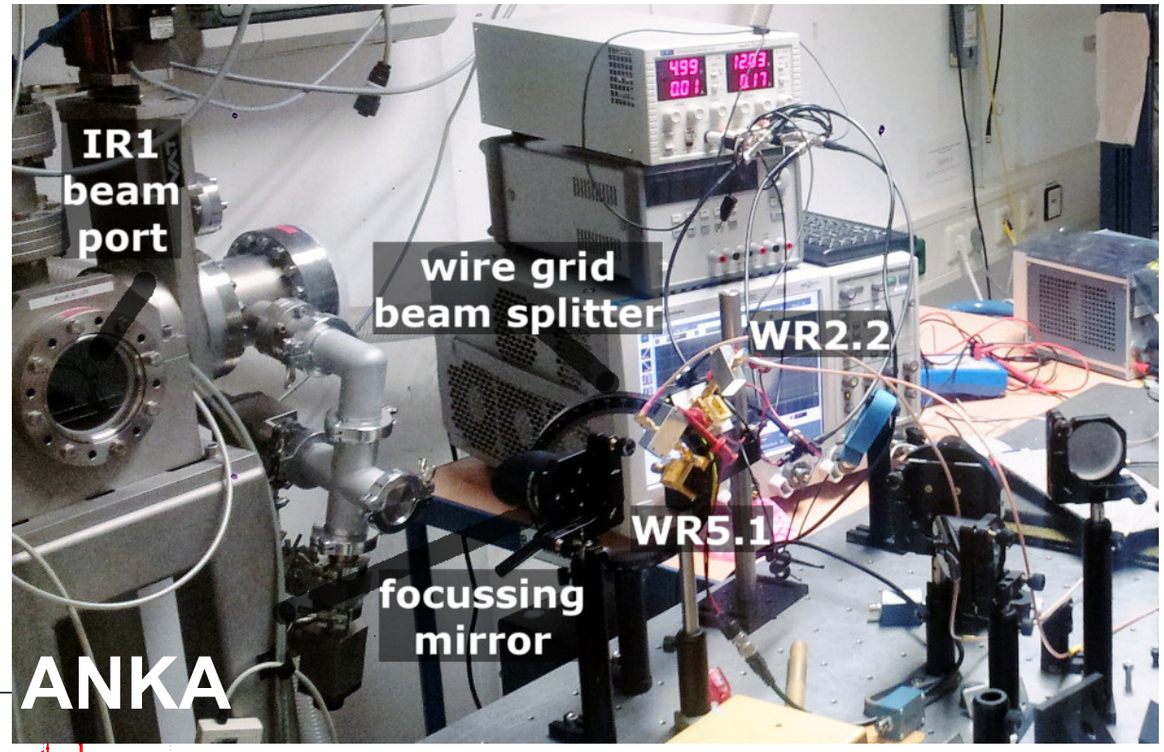
A. Finn et al., IPAC 2016, MOPMR036
A. Finn et al., IPAC 2015, MOPTY080

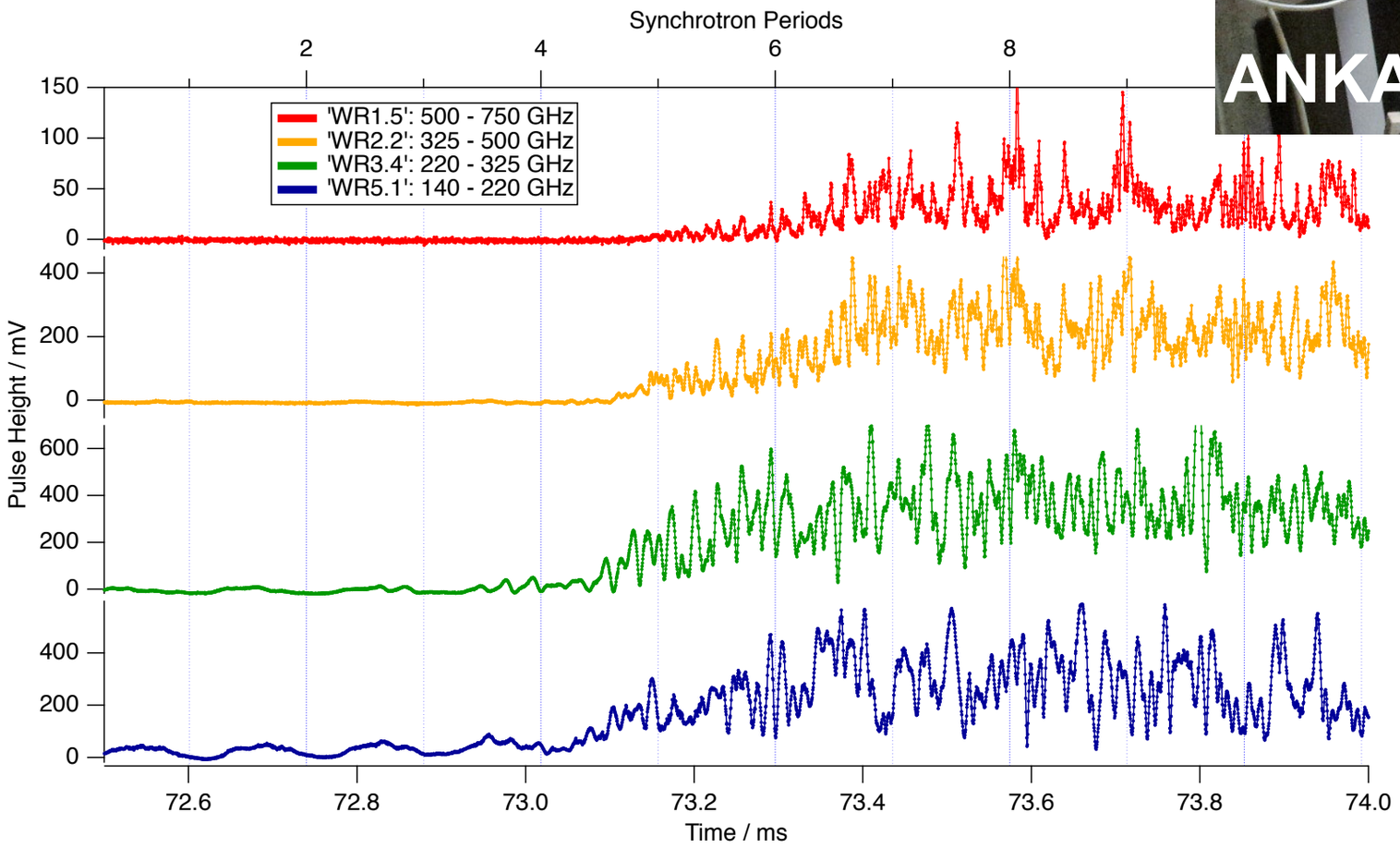




Single-shot spectrometer

- Zooming into the bursts
  - Different behavior in different frequency ranges



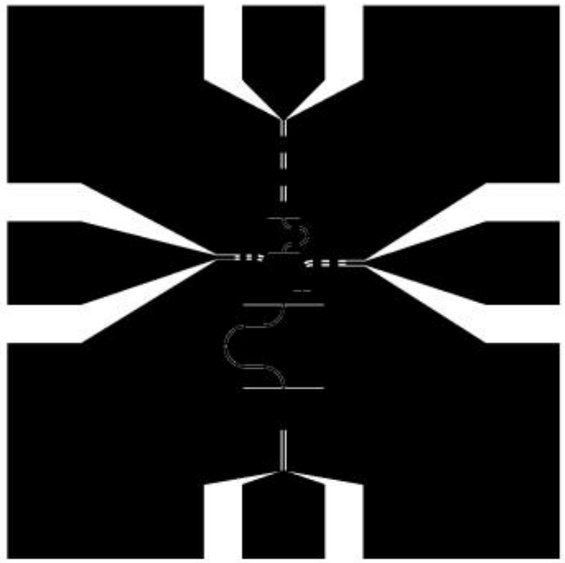


courtesy J. Steinmann

Single-shot spectrometer

- Integrated planar array of double-slot antenna- coupled YBCO detectors

3 mm by 3 mm four-element array

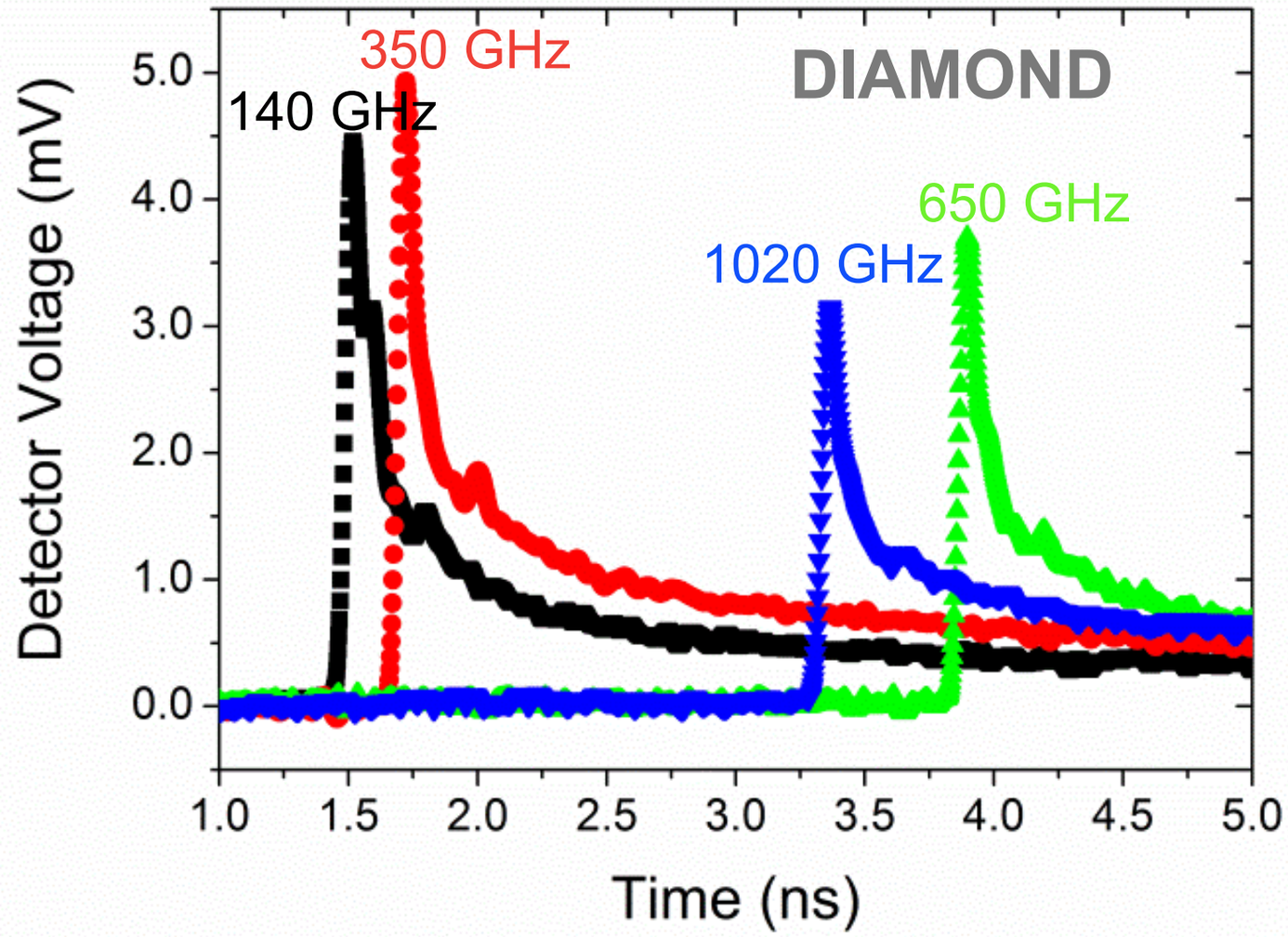


detector block

Poster J. Raasch et al. IBIC 2016, WEPG56

A. Schmid et al., ASC2016

single bunch in the Diamond LS filling pattern
simultaneously measured with all array channels



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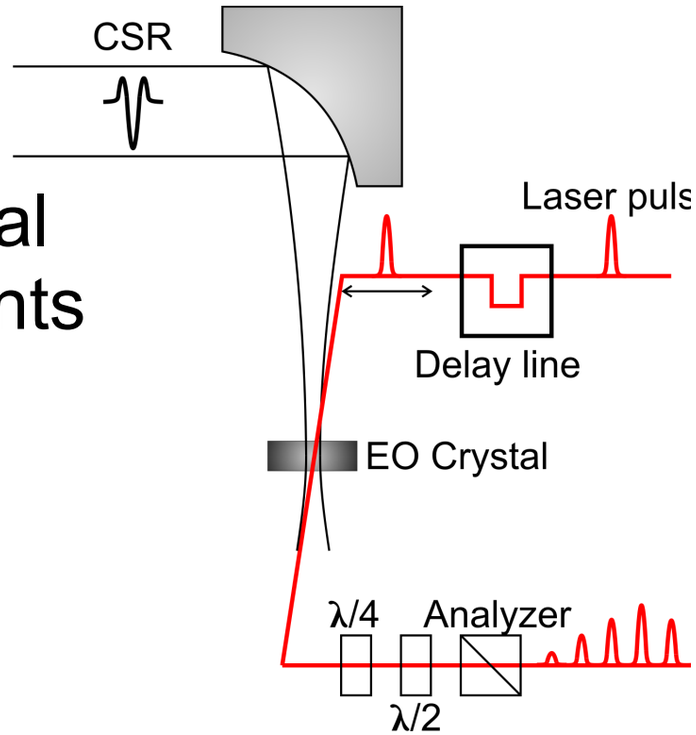
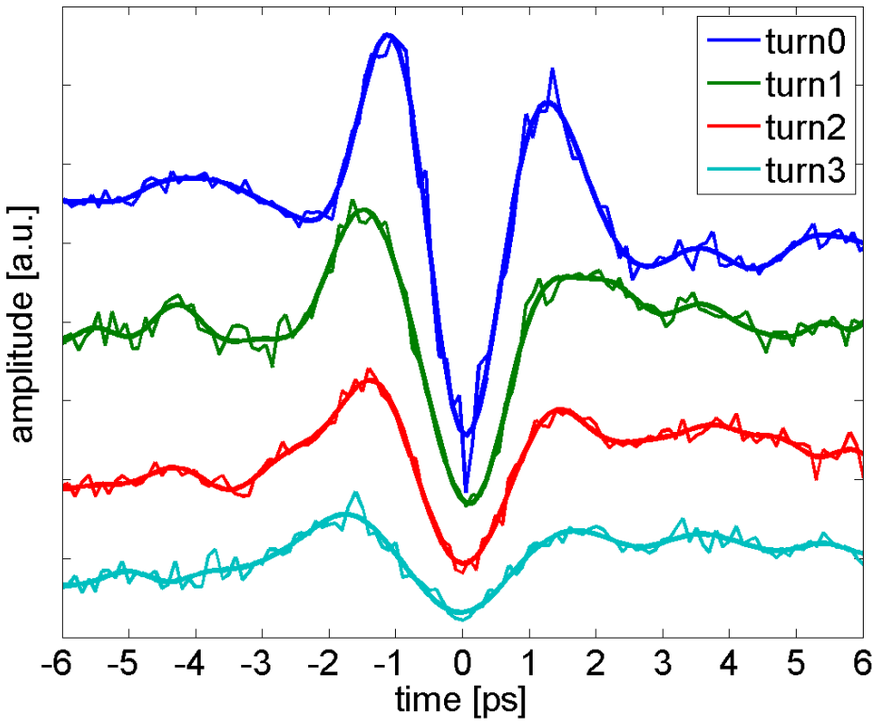
EO techniques at storage rings: first experiments

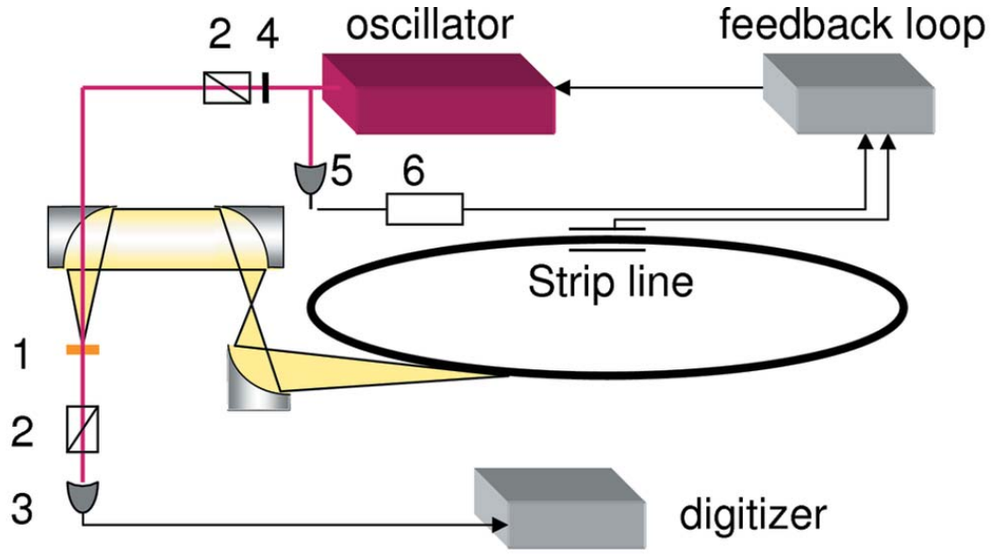
- SLS, FEMTO slicing experiment: EO sampling & EO spectral decoding measurements of CSR from ‘sliced’ bunch



F. Müller et al., FEL2010, WEPA10

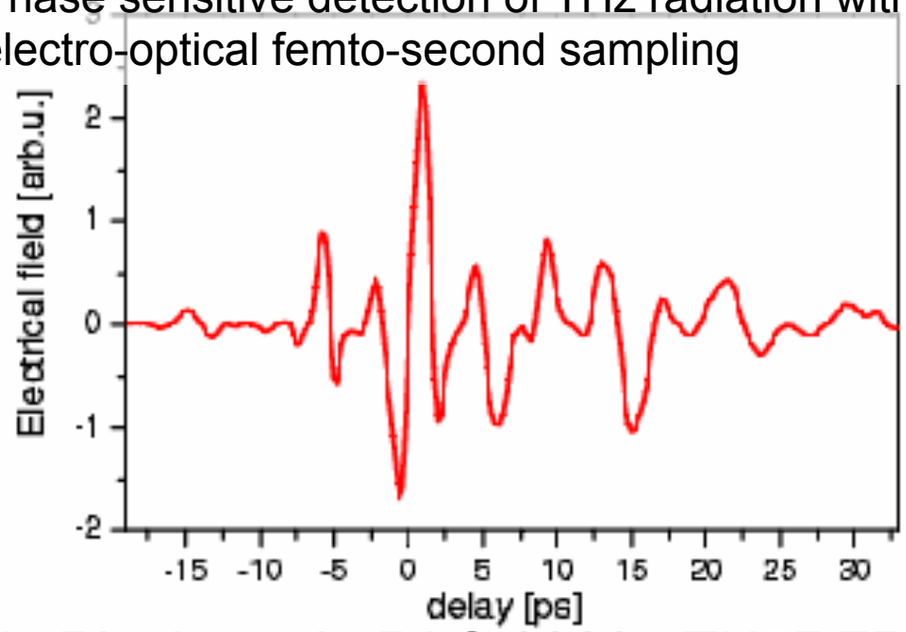


- ANKA: asynchronous sampling



S. Ibrahimkutty et al., J. Synchrotron Rad. (2011)18

Phase sensitive detection of THz radiation with electro-optical femto-second sampling



A. Plech et al., PAC 2009 , TU5RFP026

EO in the far field: dynamics at large time scales

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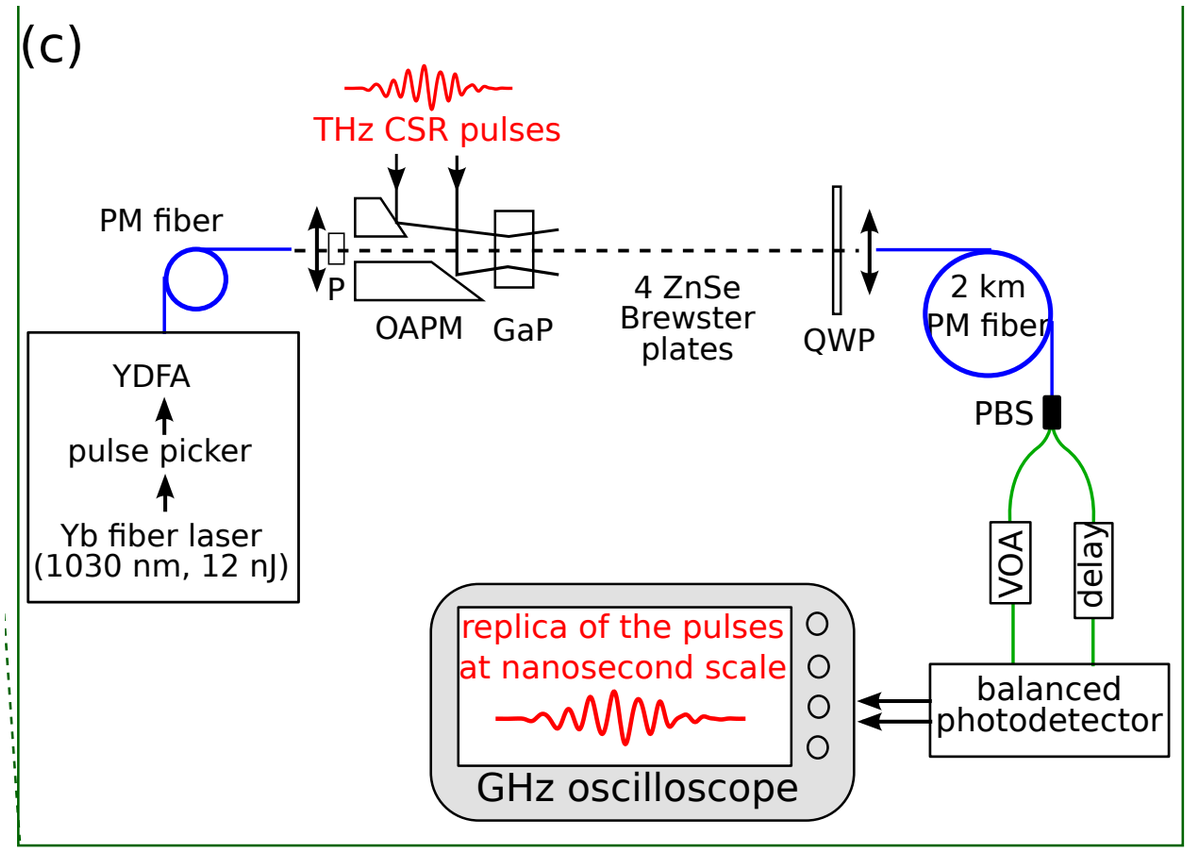
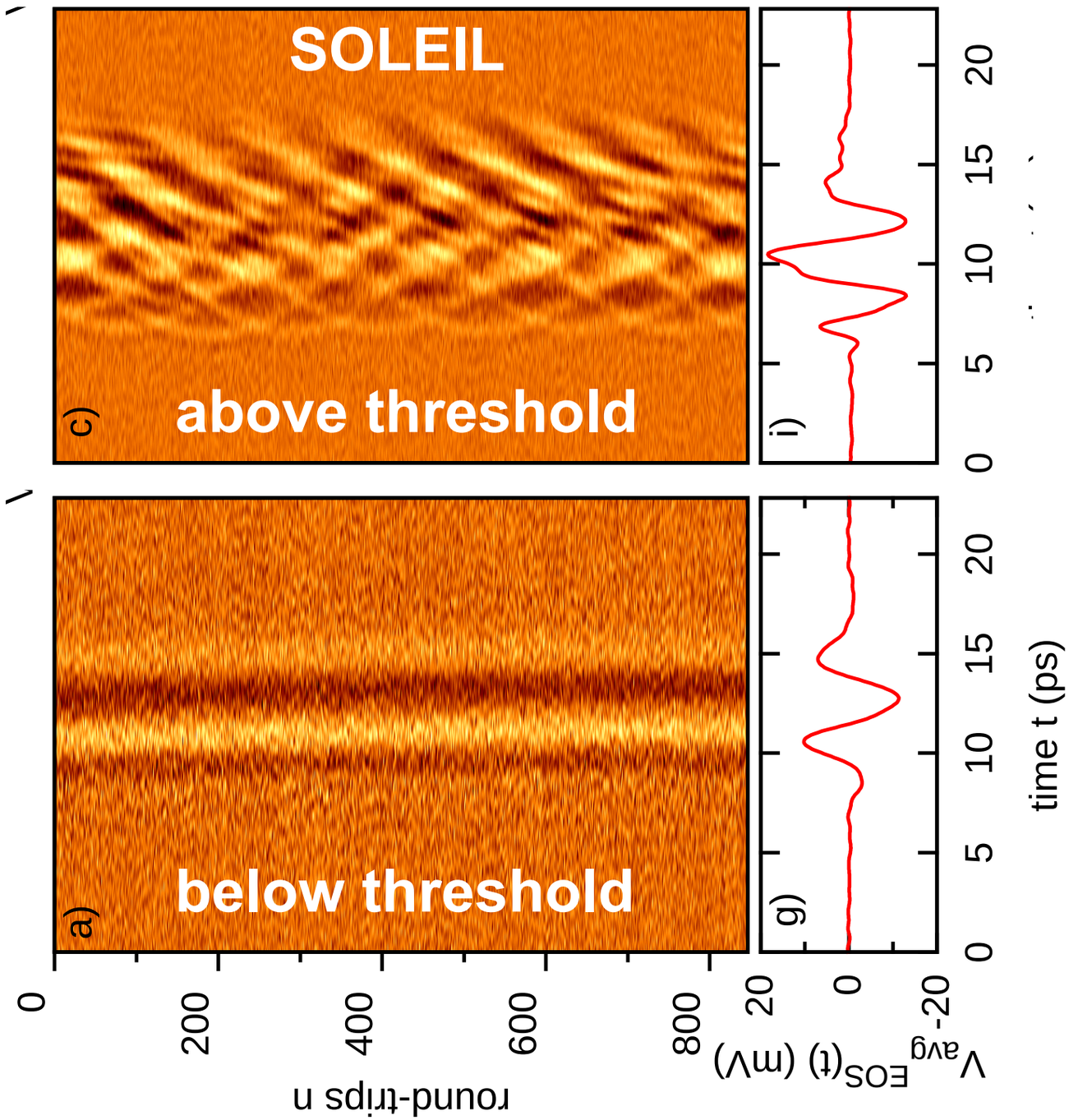
high-sensitivity photonic time-stretch EO sampling



C. Evain, et al., arXiv:1607.08072 (2016)
C. Szwaj, et al., arXiv:1607.07168 (2016)

THz pulses shapes vs time



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EO in the near field

Electro-Optical Spectral Decoding

Unmodulated chirped laser pulse

Int.

$\Delta\lambda \sim \Delta t$

t

Laser pulse modulated with the electric near-field of bunch

$\Delta\lambda$

Spectrometer

Polarizer

Crossed polarizer

EO-crystal

Electron bunch

Storage ring

Single-shot bunch profiles

Int.

t

Laser beam path

Electron beam direction

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courtesy N. Hiller, P. Schönfeldt

EO in the near field

Electro-Optical Spectral Decoding

Unmodulated chirped laser pulse

Int.

$\Delta\lambda \sim \Delta t$

t

Laser pulse modulated with the electric near-field of bunch

$\Delta\lambda$

Spectrometer

Polarizer

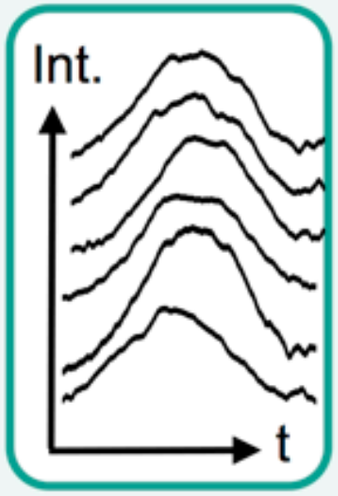
Crossed polarizer

EO-crystal

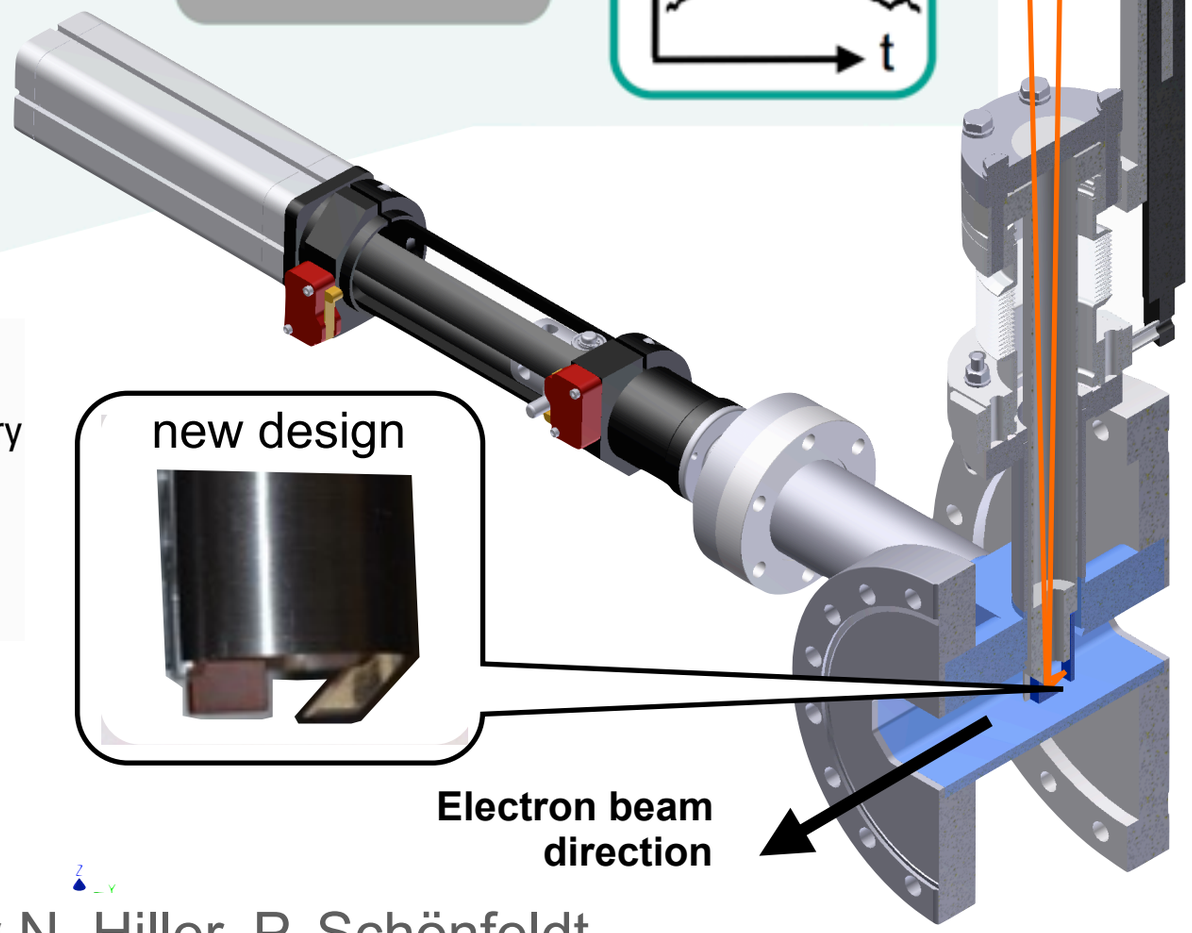
Electron bunch

Storage ring

Single-shot bunch profiles



Laser beam path



new design

Electron beam direction

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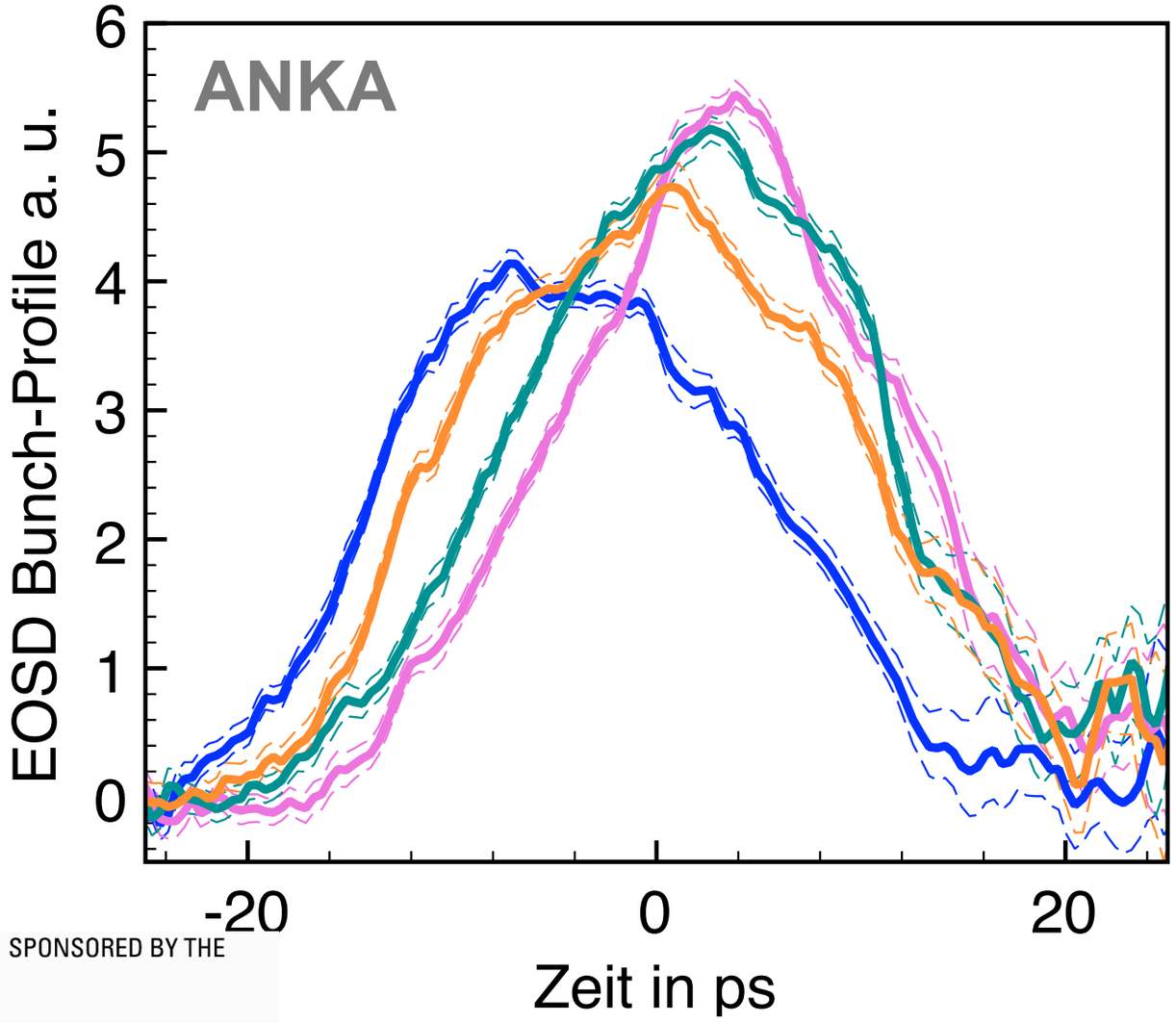
courtesy N. Hiller, P. Schönfeldt

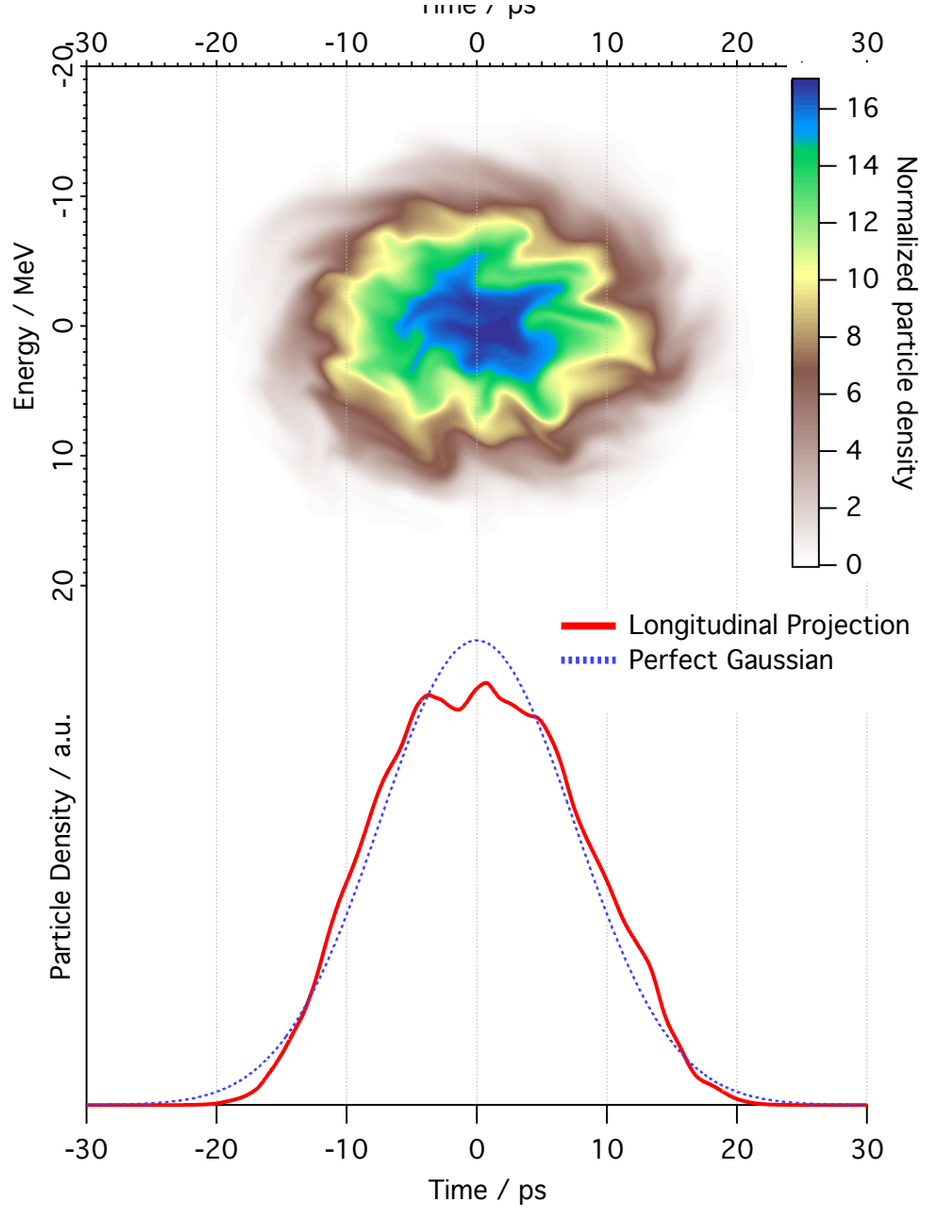
EO in the near field: bunch shape dynamics

- Single-shot EOSD measurements show dynamic sub-structures



N. Hiller, et al., IBIC 2014, MOPD17

simulated phase space



courtesy J. Steinmann, P. Schönfeldt

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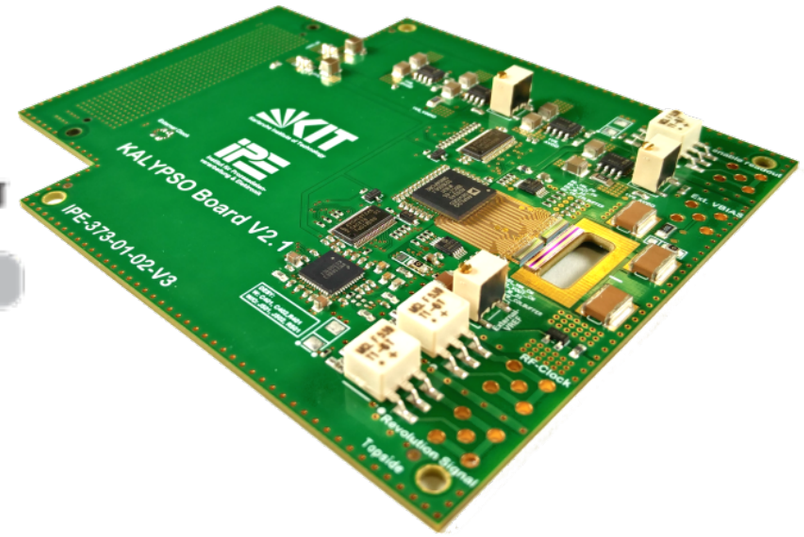
KALYPSO: KArlsruhe Linear arraY detector for MHz-rePetition rate SpectrOscopy



- Scientific goal: develop the “ideal” detector for EOSD measurements:
  - High-repetition rate single-shot resolution
  - Continuous data acquisition ➜ turn-by-turn monitoring over > 10^6 turns
  - Detect radiation in visible & near-infrared spectrum
  - Real-time data analysis ➜ FPGA / GPU heterogeneous DAQ

Poster M. Vogelsanget al. IBIC 2016, WEPG07

- Main technological challenges:
  - Fast front-end electronics: GOTTHARD chip
  - High density connections (wire-bondings, transmission lines, etc.)
  - High-throughput DAQ system

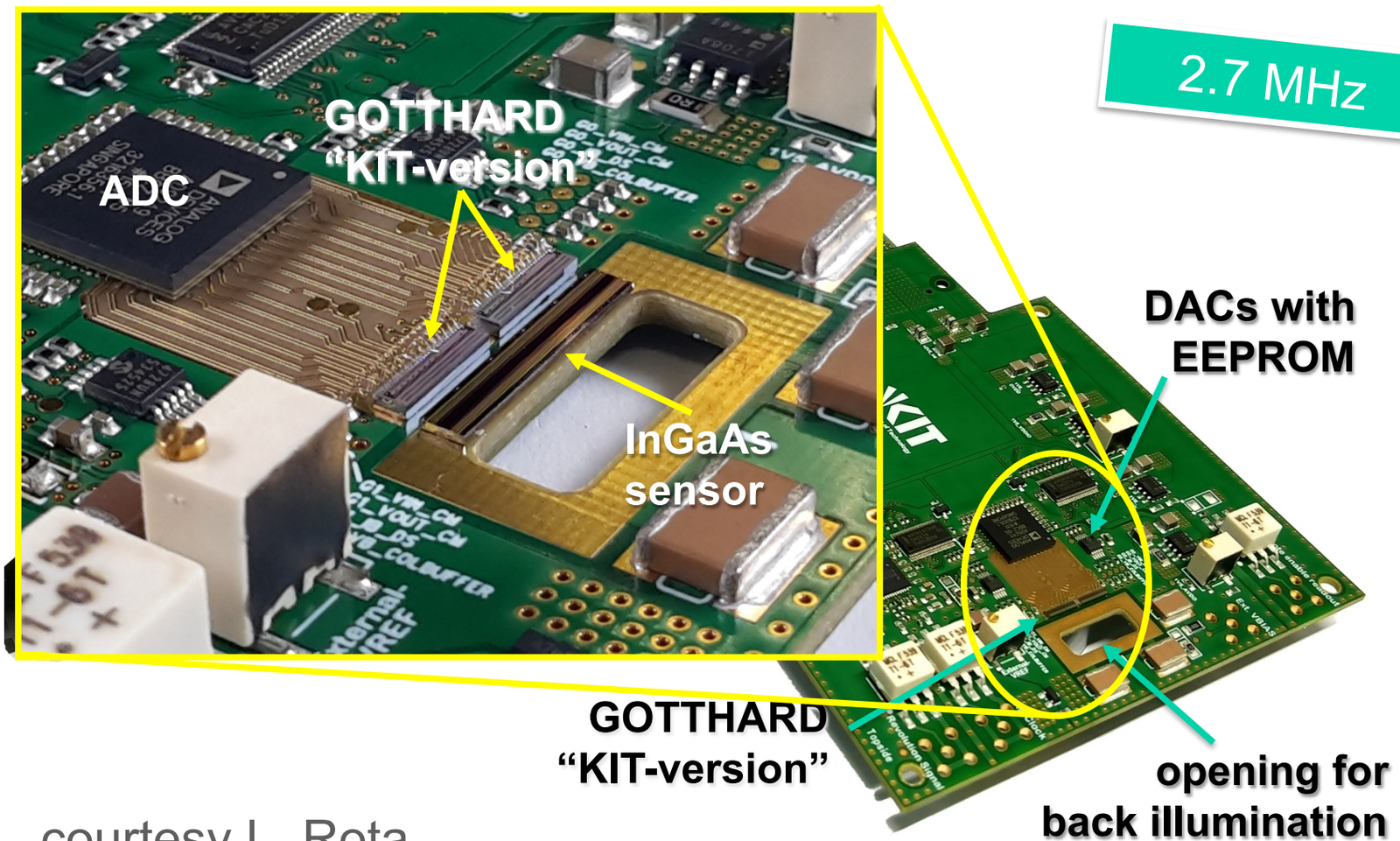
courtesy L. Rota

KALYPSO: KArlsruhe Linear arraY detector for MHz-rePetition rate SpectrOscopy

- Readout rate of commercial InGaAs spectrometers is limited to ~100 kHz

Poster L. Rota et al.
IBIC 2016, WEPG46

KALYPSO: a 2.7 Mfps linear-array detector for visible to NIR radiaton



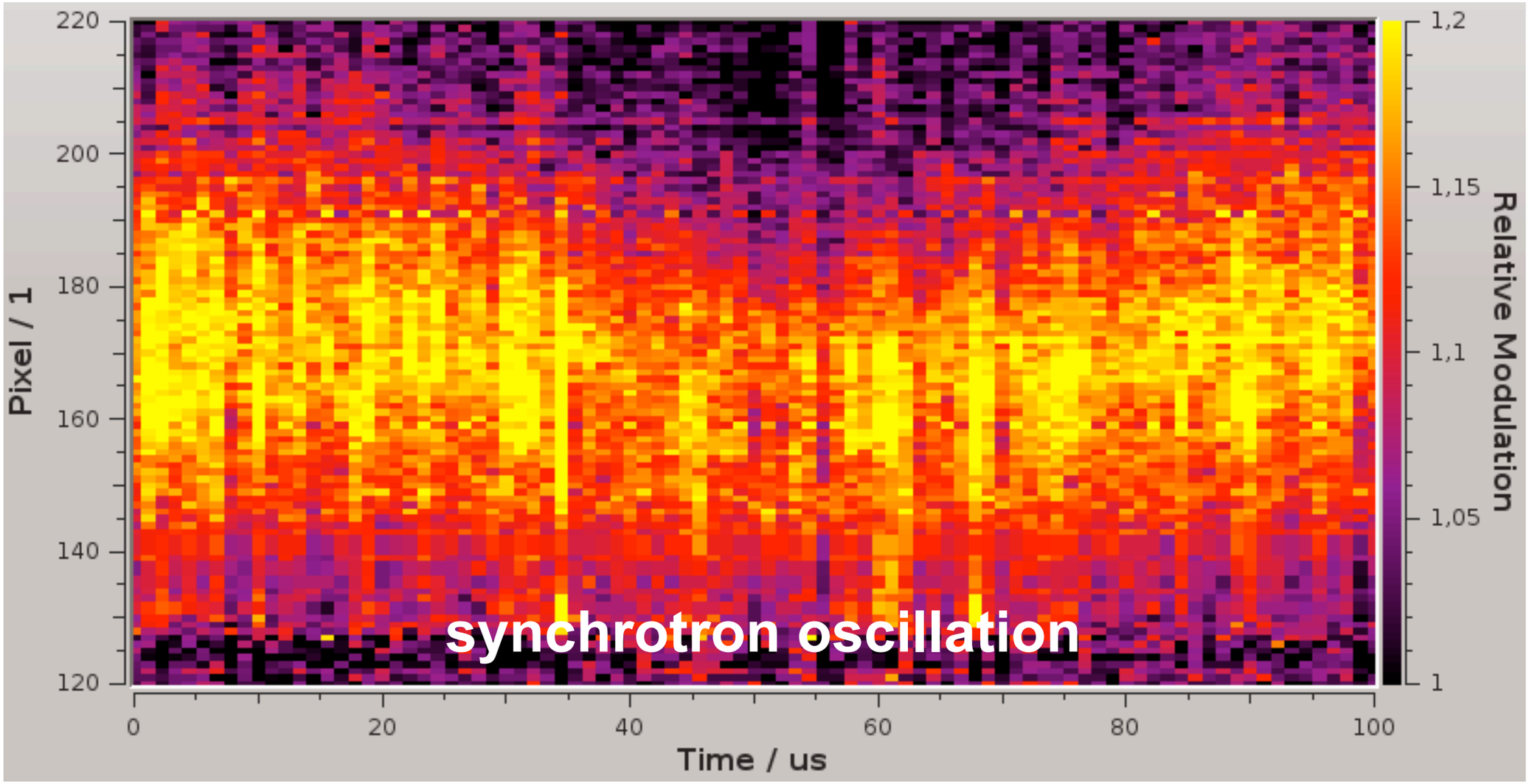
courtesy L. Rota

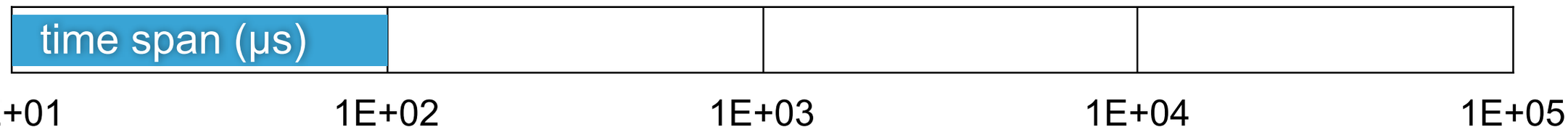
- Aim: 2.7 MHz (XFEL 5 MHz)
- Applications: turn-by-turn long. & transv. profiles

Single-shot bunch profiles with EO & KALYPSO

- Acquisition rate: 900 kHz - one image every 1 µs

courtesy P. Schönfeldt





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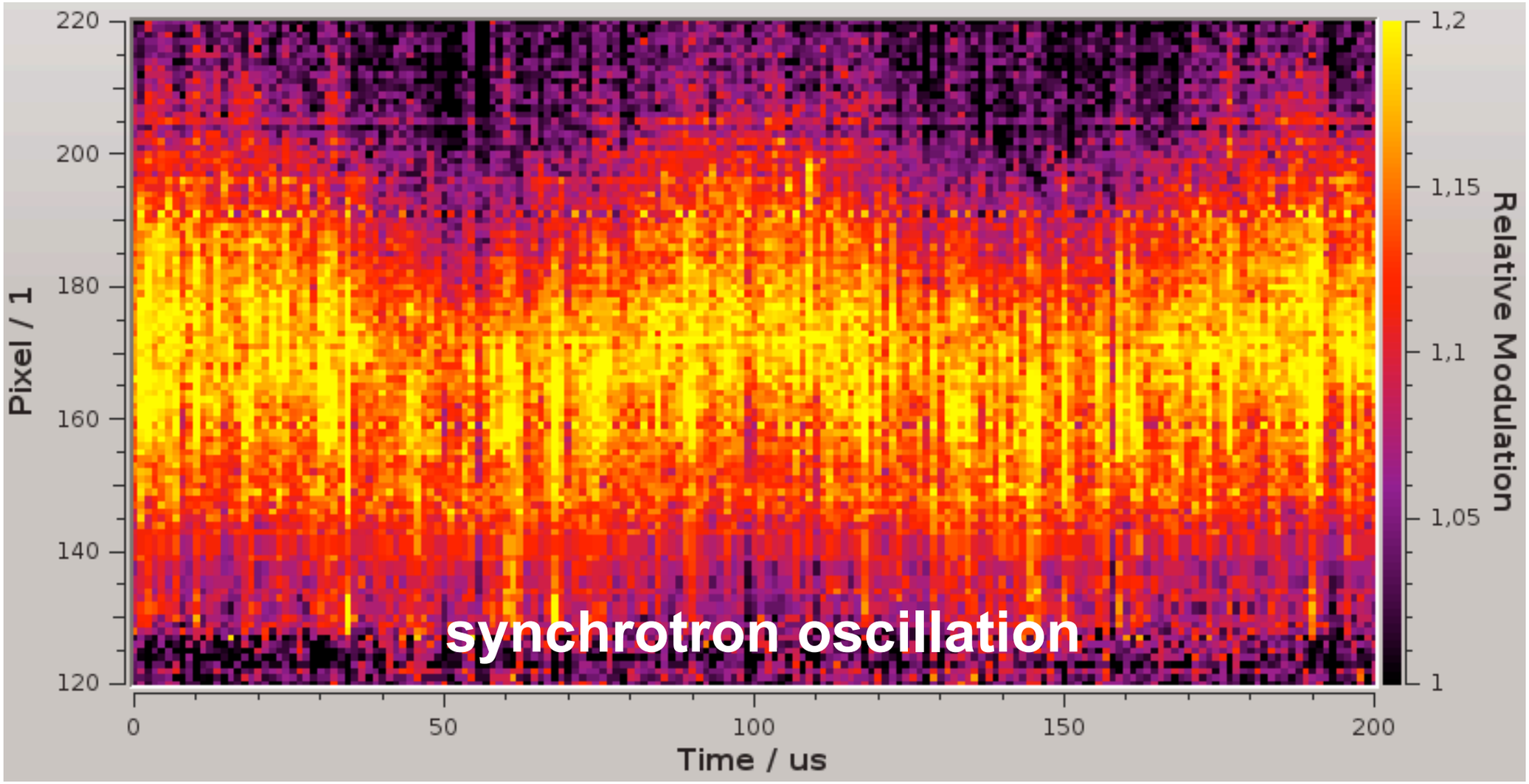
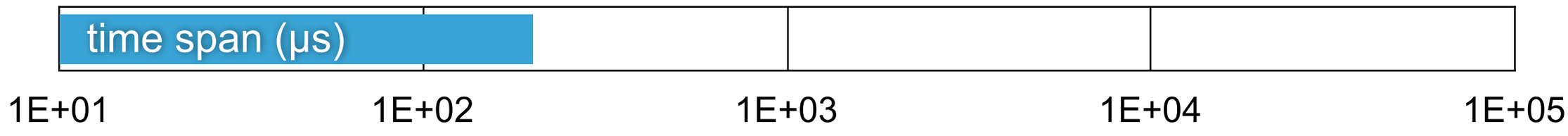
courtesy P. Schönfeldt





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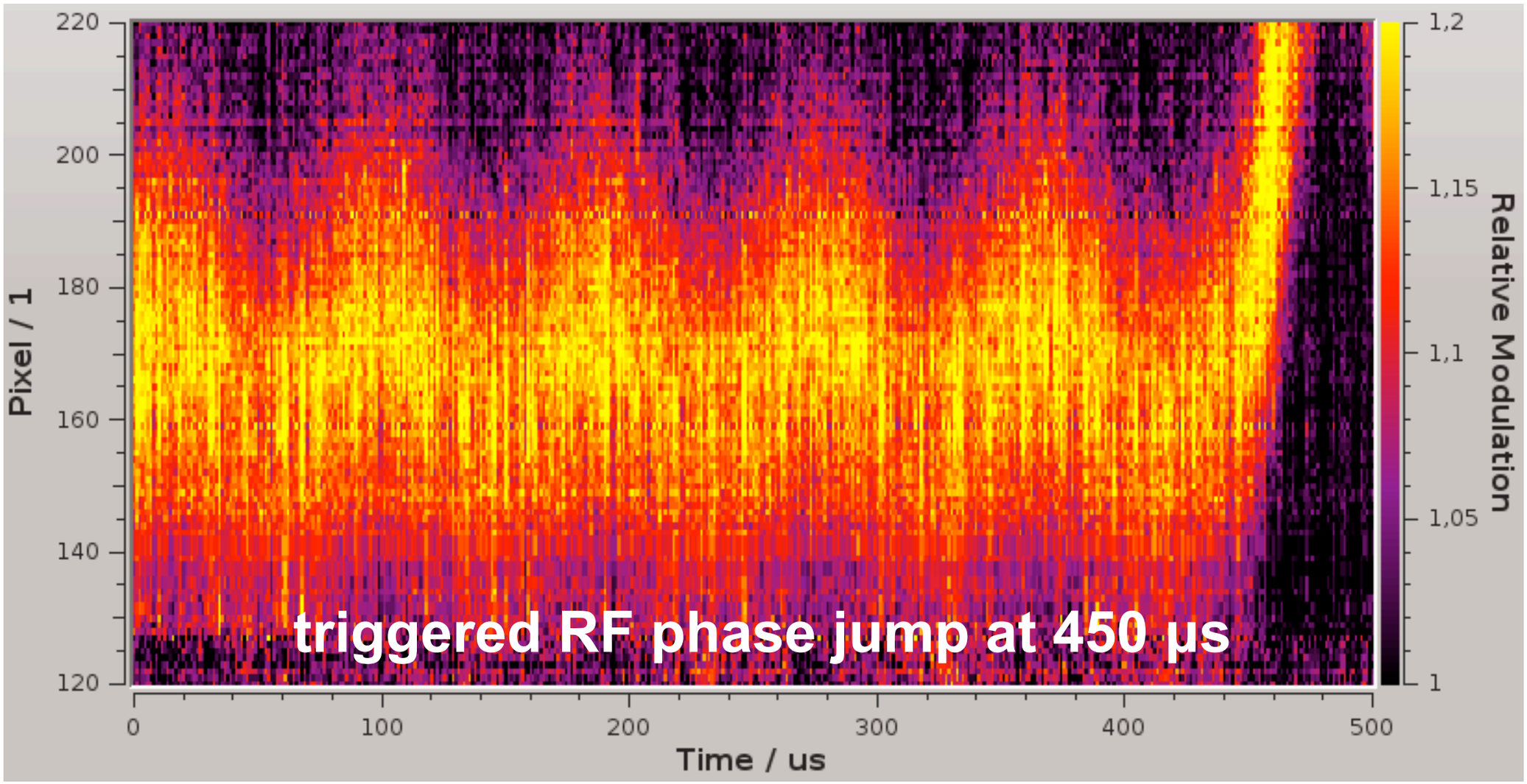
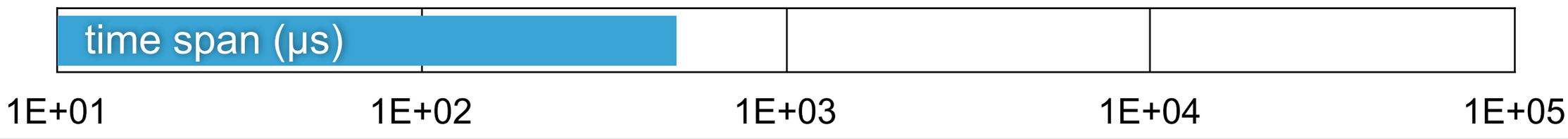
courtesy P. Schönfeldt

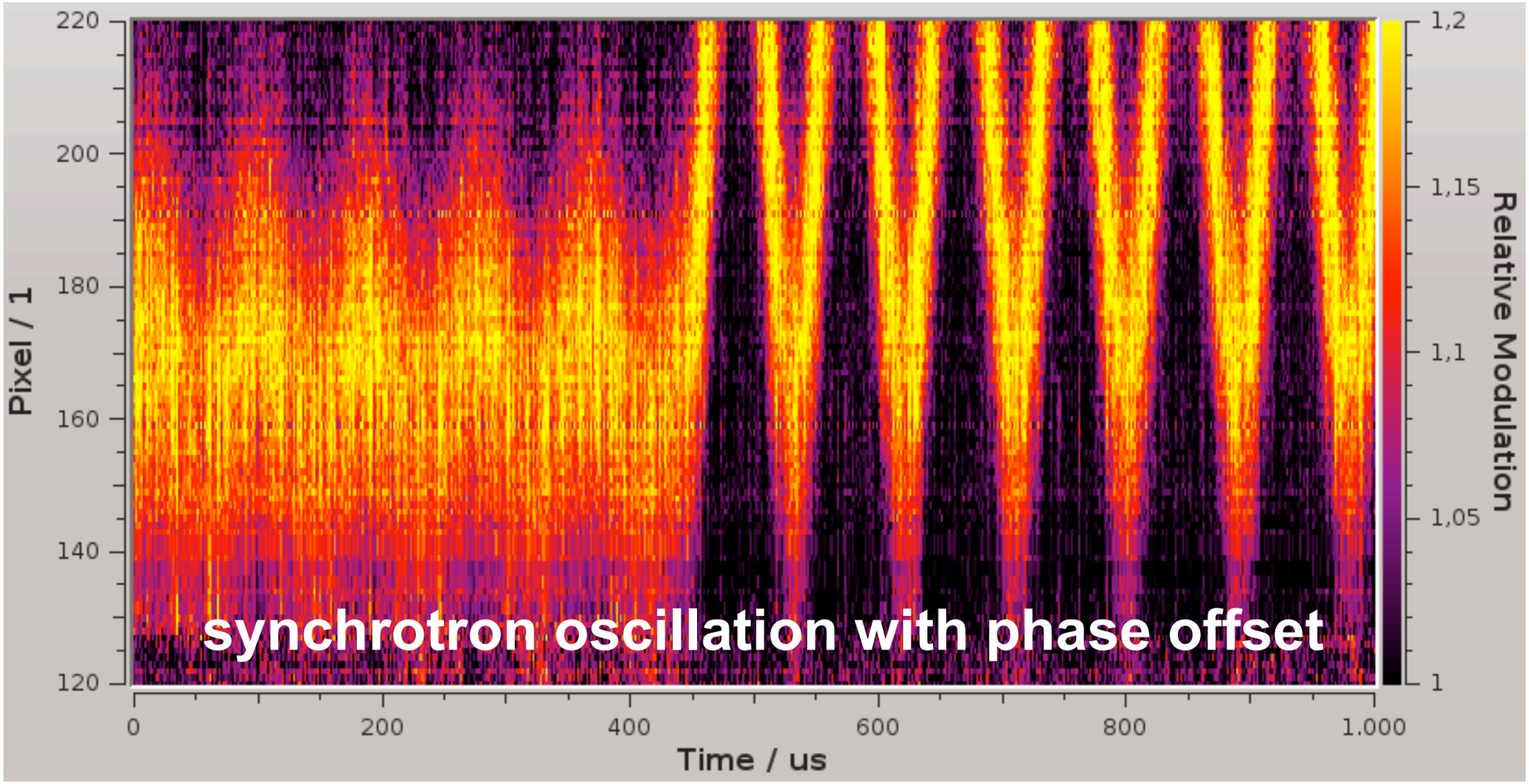


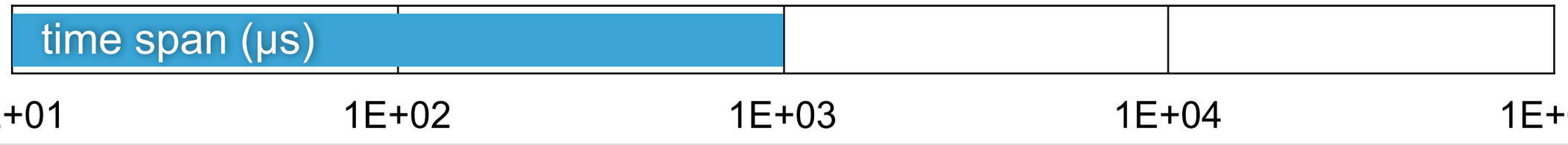


Single-shot bunch profiles with EO & KALYPSO

- Acquisition rate: 900 kHz - one image every 1 µs

courtesy P. Schönfeldt

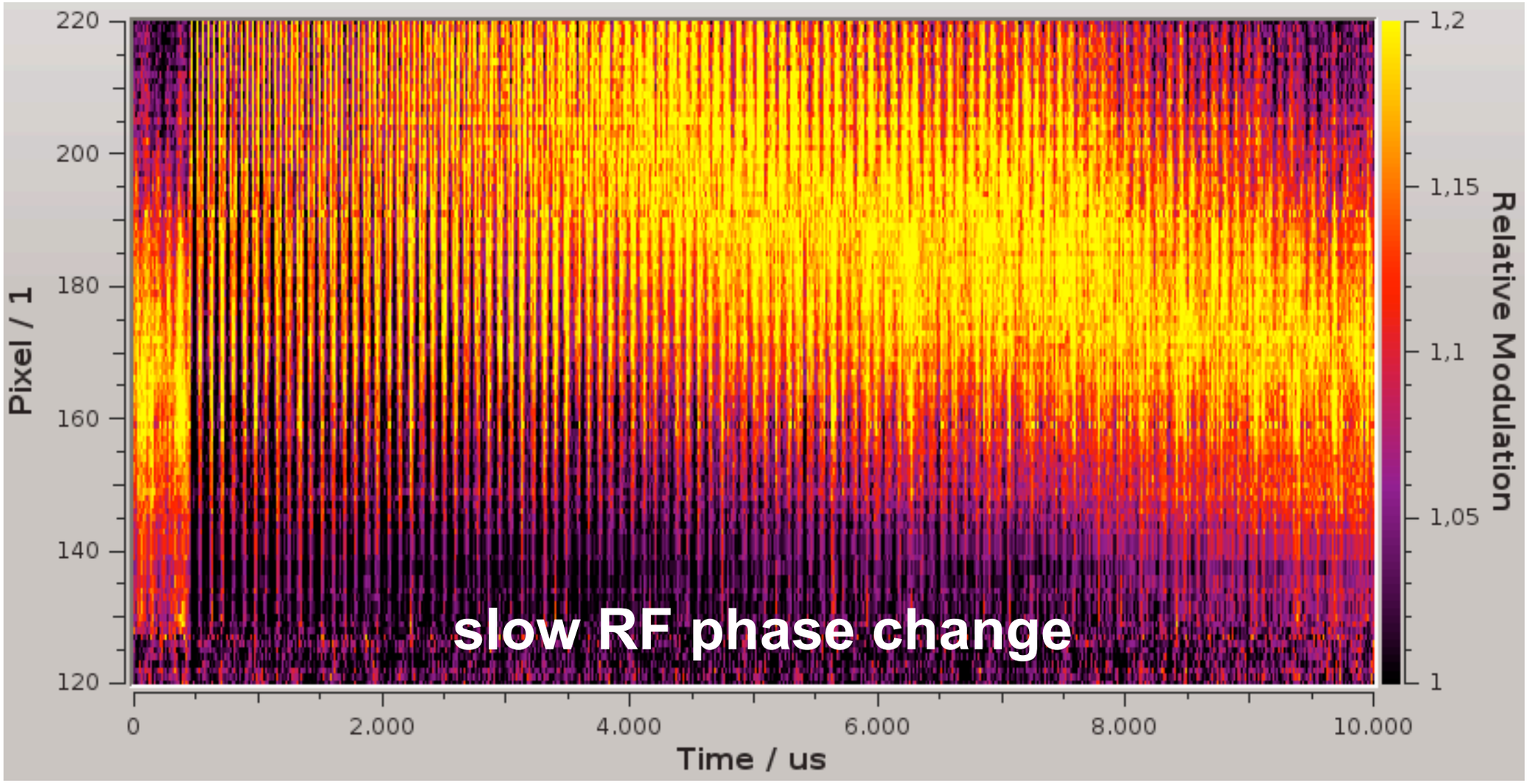


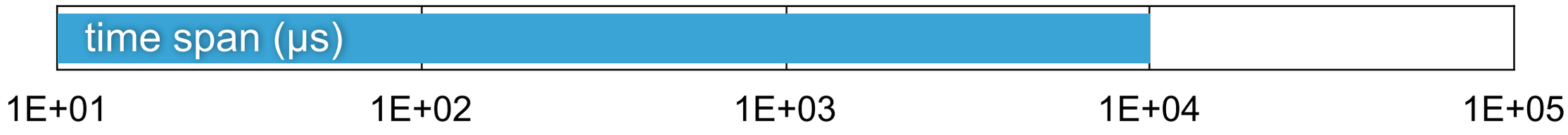


Single-shot bunch profiles with EO & KALYPSO

- Acquisition rate: 900 kHz - one image every 1 µs

courtesy P. Schönfeldt

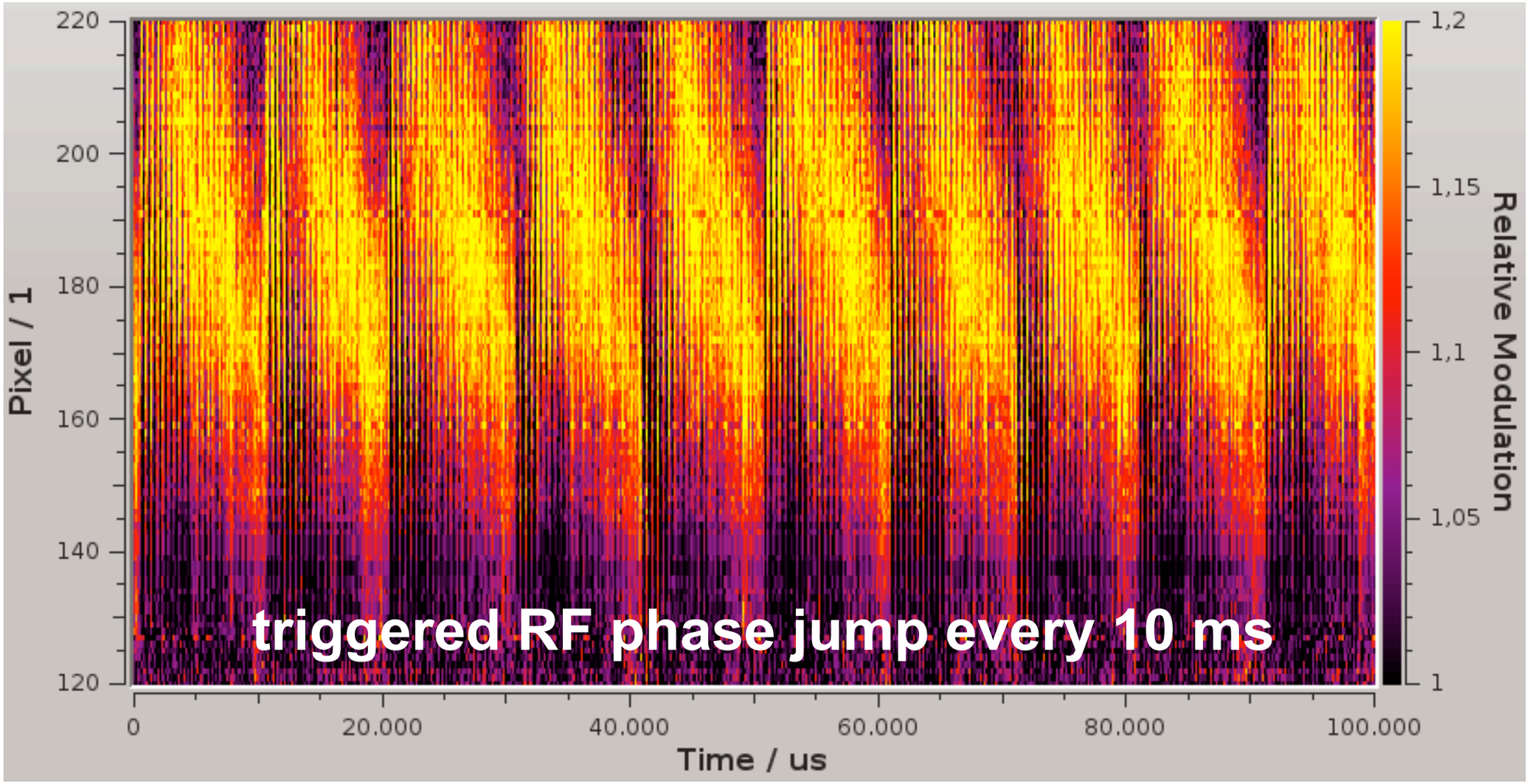


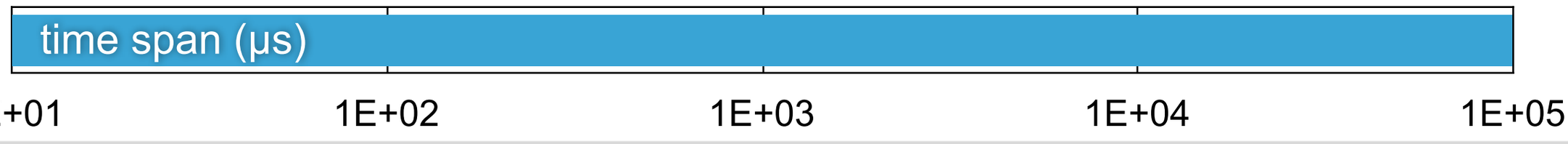


Single-shot bunch profiles with EO & KALYPSO

- Acquisition rate: 900 kHz - one image every 1 µs

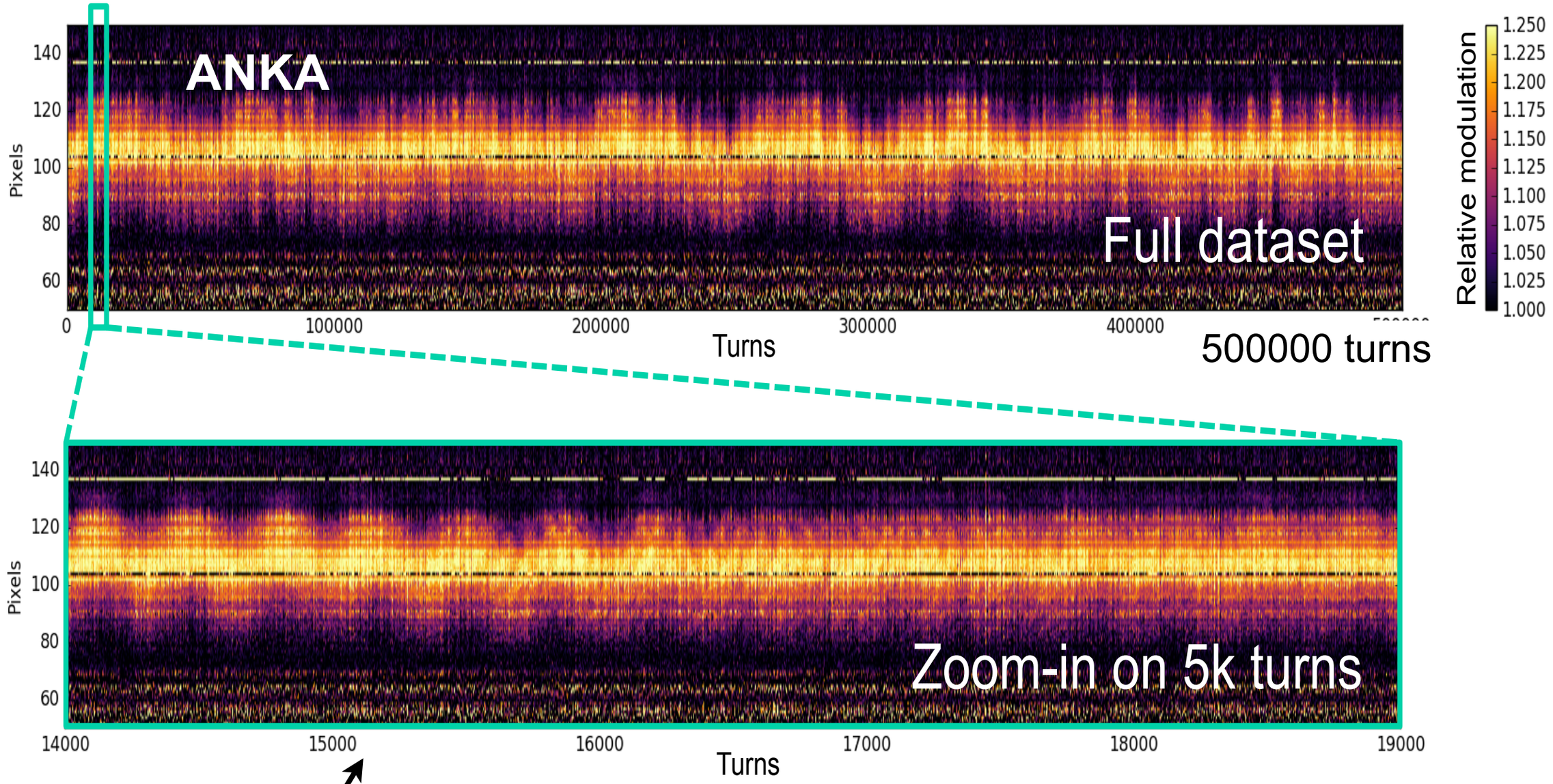
courtesy P. Schönfeldt





Micro-bunching measurements with KALYPSO

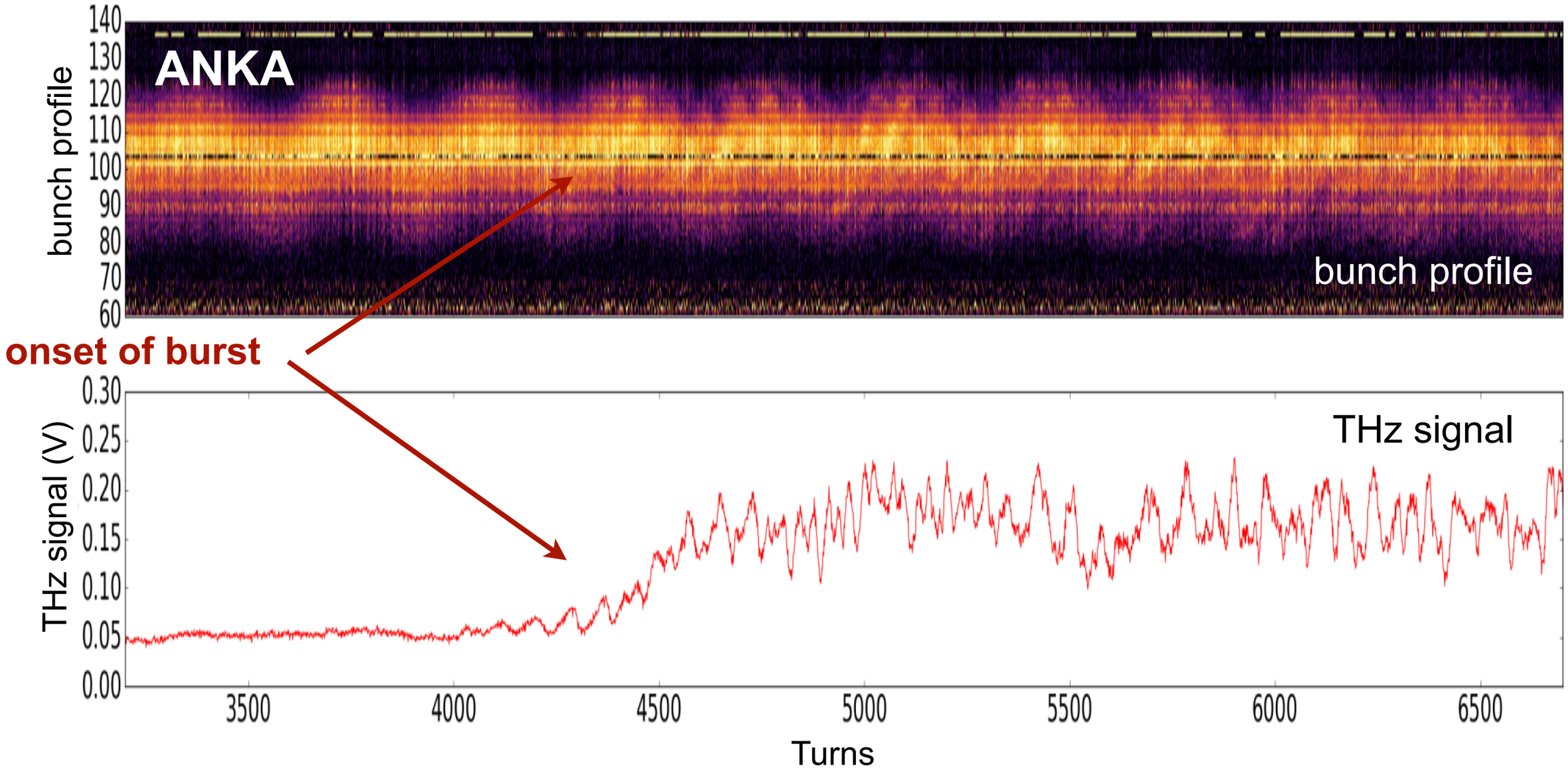
Each vertical line corresponds to a single-shot profile measurement acquired at f_{rev} = 2.7 MHz



courtesy L. Rota

Micro-bunching measurements with KALYPSO

- Synchronous measurements with KALYPSO and KAPTURE



courtesy L. Rota

Summary

- Micro-bunching measurement techniques allow to study the complex and nonlinear dynamics in longitudinal phase space
- Observation of, e.g.,
  - longitudinal bunch profiles [“direct”]
  - emitted (coherent) radiation [“indirect”]
- Diagnostics requirements:
  - high resolution (ps) - high rate (500 MHz) - long term observation (secs - hrs)
- Recent developments based on:

THz techniques time domain	**EO techniques far field**
THz techniques frequency domain	**EO techniques near field**

- Next steps?
  - combination of methods?

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- T. Boltz, M. Brosi, F. Rämisch, M. Schuh, P. Schönfeldt, M. Schwarz, J. Steinmann, and the rest of the ANKA THz team
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